ILLUMINATING ENGINEERING

PREPARED BY A STAFF OF SPECIALISTS

FOR STUDENTS AND ENGINEERS

EDITORS

FRANCIS E. lmore CADY, B.S.

National Lamp Works of General Electric Company

HENRY B. DATES, E.E.

Professor of Electrical Engineering, Case School of Applied Science

CONTRIBUTORS

L. J. BUTTOLPH	HOWARD LYON
F. E. CADY	H. H. MAGDSICK
P. W. COBB	W. R. MOTT
WARD HARRISON	I. H. VAN HORN
M. LUCKIESH	A. G. WORTHING

NEW YORK

JOHN WILEY & SONS, INC.

LONDON: CHAPMAN & HALL, LIMITED

1925

Stanhope Press
TECHNICAL COMPOSITION COMPANY
F. H. GILSON COMPANY
BOSTON, U. S. A.

CONTRIBUTORS

A. G. WORTHING, Ph. D., Physicist, Nela Research Laboratory, Nela Park, Cleveland, Ohio. — *Physics of Light Production,* Chapter I; portions of Chapter II.

HOWARD LYON, A. B., M. S., Chemical Engineer, The Welsbach Company. — *Gas,* Chapter II.

W. R. MOTT, B. S., M. S., Formerly Chemist, Union Carbide and Carbon Research Laboratories, Inc. — *Arc Lamps,* Chapter II.

I. H. VAN HORN, B. S., Engineer-Physicist, National Lamp Works of General Electric Company. — *Electric Incandescent Lamps,* Chapter II.

L. J. BUTTOLPH, A. B., M. S., Engineer, Cooper-Hewitt Electric Company. — *Vapor Tube Lamps,* Chapter II.

F. E. CADY, B. S., Manager of the Research Service Department, Nela Park, Cleveland, Ohio. — *Photometry,* Chapter III.

P. W. COBB, M. D., Psychologist, Lighting Research Laboratory, Nela Park, Cleveland, Ohio. — *Physiological Optics,* Chapter IV.

WARD HARRISON, M. E., Illuminating Engineer, National Lamp Works of General Electric Company. — *Fundamental Principles of Illuminating Engineering,* Chapter V; *Commercial Lighting,* Chapter X; *Street Lighting,* Chapter XIII.

M. LUCKIESH, B. S., M. S., Director of the Lighting Research Laboratory, National Lamp Works of General Electric Company. — *Light, Shade and Color,* Chapter VI; *Daylight,* Chapter VII; *Residence Lighting,* Chapter VIII; *Lighting of Public Buildings,* Chapter IX.

H. H. MAGDSICK, B. S., Engineer, National Lamp Works of General Electric Company. — *Industrial Lighting,* Chapter XI. — *Sign and Display Lighting,* Chapter XII. — *Light Projection,* Chapter XIV.

PREFACE

In 1918 there was established at Case School of Applied Science, with the coöperation of the Management of the National Lamp Works of the General Electric Company, a course in Illuminating Engineering designed especially for undergraduate students.

This book is, therefore, the result of six years of actual experience in the presentation of this subject in the classroom. It deals with the principles underlying the production of light and its applications, rather than the details of the applications themselves, since these are subject to change due to the rapid development of this branch of engineering.

The course as given at Case School of Applied Science covers a period of one year. Three hours per week are assigned in part to lectures and in part to recitations, and one period per week is devoted to laboratory work. The lectures are given by specialists in their respective subjects and the recitation work is conducted by a member of the departmental staff.

In the preparation of this book, space limitations have made it necessary to omit much material which might otherwise have been included, and there is no thought that the subject is treated exhaustively.

The material has been drawn from such a large number of sources, including many of the technical and scientific journals, that individual acknowledgment has seemed to be impracticable. However, in connection with the different subjects, some references have been inserted to show where additional information is available, and the more important tables have been included as giving data not always readily accessible.

In the preparation of the material for publication it was necessary to adopt a somewhat different arrangement than has been followed in the lectures themselves, in order to bring all material on a given subject together and to avoid duplication. In many instances, therefore, material of one contributor has been combined with that of another. The major subject of each contributor is given in the list of contributors, but it has not been found practical to identify each contribution in detail.

The editors desire to record their appreciation of the invaluable assistance and most hearty coöperation their associates have rendered. It is through their most generous assistance and contributions that this book is possible.

INTRODUCTION

Illuminating Engineering had its inception as a separate engineering profession in the organization, in 1906, of the Illuminating Engineering Society. Since that time various treatises on the subject have been published, some definitely intended as textbooks; but the science and art of illumination are so new, and the subject matter so diverse, that none of the authors of these treatises would lay claim either to comprehensiveness or to thoroughness. Recognition of the broad scope of the subject was first secured through the course of lectures given at the Johns Hopkins University in the fall of 1910. Since that time both the science and the art have developed rapidly through the combined efforts of a great variety of workers in different fields; and, even now, he who would seek, single-handed, to prepare an inclusive treatise on Illuminating Engineering, as it is understood and practiced to-day, would find his task a difficult one.

When, therefore, Case School of Applied Science secured the coöperation of the Managers of the National Lamp Works of the General Electric Company in the inauguration of a course in Illuminating Engineering, it was sought to have each aspect of the subject presented by a specialist. Most of the subjects have been presented by specialists of the National Lamp Works, but certain subjects, viz., Gas Lamps, Arc Lamps and Vapor Tube Lamps, have been given by specialists of other organizations, through the courtesy of the Welsbach Company, the National Carbon Company and its successor, the Union Carbide and Carbon Research Laboratories, Inc., and the Cooper-Hewitt Electric Company.

From the beginning it was apparent that much of the value of the course was lost owing to the unavailability of an adequate textbook. Through the insistence of Professor H. B. Dates, head of the Department of Electrical Engineering, the various lecturers were gradually induced to commit their lectures to writing, so that mimeographed copies might be distributed to the students. It was but a step in thought from this to the publication of the combined lectures in textbook form, though this step was covered only after arduous work on the part of the two editors: Mr. Francis E. Cady, who had much of the burden of detail in the daily arrangements of the course, and Professor H. B. Dates,

whose experience in engineering education made success possible in this new educational undertaking.

The present textbook is the result of these efforts, and represents the outcome of actual experience in giving the course in Illuminating Engineering to junior and senior students in Electrical Engineering in a well-established technical school. It is published for further use in Case School of Applied Science, but with the larger hope in the minds of all who have contributed to it, lecturers, editors and administrators, that it may serve in a similar way wherever this new branch of engineering may be taught, and that it also may find use as a brief, comprehensive survey of the subject matter and current practice by that larger number of students who, having finished their collegiate courses, have entered the lighting field as a vocation.

EDWARD P. HYDE,
Formerly Director of Research, National Lamp Works of General Electric Company

St. Jean-de-Luz, France
November 22, 1923.

CONTENTS

INTRODUCTION

PRINCIPLES

ILLUMINATING ENGINEERING

CHAPTER I

PHYSICS OF LIGHT PRODUCTION

[A. G. WORTHING]

Nature of Light

Corpuscular Theory. — What is the mechanism whereby the sun sends out light? The ancients advanced a corpuscular theory. The sun, and consequently any source of light, was assumed to emit streams of small material particles or corpuscles, which moved ordinarily in straight lines and produced vision upon entering the eye. Bodies were supposed to be rendered visible by the corpuscles reflected from them. This theory was generally accepted previous to the early decades of the nineteenth century.

Wave Theory. — The idea of light as a wave phenomenon was first suggested by Huyghens in 1678. A century and a half later, on that basis, Young, Fresnel and their co-workers explained the phenomena of interference, diffraction and polarization. However, the conflict, with the earlier theory, bitterly contested and intensely dramatic, did not close until 1850 when Foucault showed, contrary to the prediction of the corpuscular theory, the velocity of light to be less in water than in air.

Transmission of light by wave motion required the postulation of a medium between sun and earth and throughout interstellar space. This medium was called the ether and was pictured, and still is by those who believe in its existence, as " a universal medium filling all known space, in which the minute portions of ordinary matter are supposed to exist not unlike the motes of dust one sees in the air of a room when a ray of sunlight enters." The main characteristic of the ether is the property of transmitting transverse vibrations with a velocity of 300,000 kilometers per second (186,500 miles per second). These vibrations were originally supposed to be mechanical, somewhat like water waves.

Electromagnetic Theory. — The great achievements of the first half of the nineteenth century regarding the nature of light were accom-

panied by similarly great achievements in the study of electricity and magnetism. In order to explain the transference of energy from one electrical circuit to another by means of their mutual inductance, it was necessary to assume an unknown medium which could be and was identified with the ether of light phenomena. In the decade following 1860, Maxwell, a great English physicist, expressed this relation definitely in a theory which treated light phenomena as purely electromagnetic. Shortly afterwards, this theory was verified experimentally by Hertz. He detected waves of purely electromagnetic origin, which possessed the velocity of light and could be reflected, refracted, scattered and polarized. These waves differed from light waves apparently only in having much greater wave-lengths.

This theory is not to be viewed as antagonistic to the wave theory developed earlier but as a very fundamental extension of it. Transverse vibrations in the ether were assumed for the propagation of electromagnetic waves as they had been assumed for the earlier wave theory; but the processes imagined had not the earlier simplicity.

Quantum Theory. — The present quantum theory is similarly to be regarded as a fundamental extension of the electromagnetic theory. In 1900–1901, it was advanced by Planck in his theoretical derivation of an expression which successfully describes the radiation from a complete radiator or black body (to be discussed later). The main departure from previous procedure consisted in the assumption of a spasmodic radiation of energy in bundles, or quanta, by the ultimate radiators, instead of a gradual, steady process.

Planck postulated (1) that the ultimate sources of light are linear oscillators, "each consisting of two poles, with equal quantities of electricity of opposite sign, which may move relatively to each other on a fixed straight line, the axis of the oscillator" (the present conception of an ultimate source of light differs from this somewhat); (2) that each linear oscillator, at least for a given condition of surroundings, possesses a definite natural frequency of vibration; (3) that an oscillator does not emit radiation or light continuously, but in brief spasmodic pulses at times when the total energy of vibration happens to be an integral multiple of the "quantum of energy" (to be defined) for the oscillator in question; and (4) that when radiation occurs it is complete in the sense that the oscillator emits the whole of its supply. The "quantum of energy" was defined by $\epsilon = h\nu$, where ϵ represents a quantum of energy for the particular oscillator, ν its natural frequency and h a universal constant of nature. According to the third postulate, radiation was not assumed to occur always when the total energy of the oscillator had reached, by some means, a single quantum, though it

might occur then. However, when emission did take place, it was necessary for the total energy of the oscillator to be some integral number of quanta.

Peculiarly enough, while clarifying and unifying much of physics that was not understood or stood disconnected, the quantum theory has not been successful in some instances in accounting for phenomena that had appeared simple on the electromagnetic wave-theory basis. It is difficult to reconcile the quantum theory explanation of ionizing and radiating potentials on the one hand with that for interference of light on the other hand. The former seems to require the propagation of radiation in quanta to restricted linear paths, the latter to outward-spreading spatial disturbances. The former pictures radiation from a light source as a barrage of energy projectiles, the latter as a succession of two-dimensional, spreading waves.

Wave-length Analysis of Radiation

The Grating. — The most common method for the determination of wave-length, which is a fundamental factor in radiation measurements, makes use of a grating. One type of grating consists of a great number of very fine equidistant parallel scratches on a glass plate. It is essentially a collection of very narrow equal slits, equally spaced, side by side. Another type consists of a piece of speculum metal similarly ruled. In the former type the spectrum is formed by the radiation transmitted by the grating; in the latter type, by the radiation reflected from the grating.

If a mercury-arc lamp in operation is viewed through a grating, several groups of colored images of the source will be seen on each side of the lamp. In the order of their distances from the lamp, the colors of the images are violet, blue, green, yellow and orange. Each group possesses the same number of colored images similarly placed and constitutes a spectrum of the source. If a linear incandescent source is viewed similarly, several broad multi-colored bands will be seen on each side of the source. Each band, analogous to a group of colored images of the mercury-arc, constitutes a spectrum of the source. In this case, the images of the source may be considered infinite in number, their combination resulting in a single multi-colored image or band changing gradually in hue from a violet at the edge next the source to a faint deep red at the far edge.

These spectra are due to diffraction, i.e., the spreading of a beam of light into a more or less diffuse fan-shaped pencil on its passage close to the edge of an obstacle or through a narrow slit.

Spectra are spoken of as of the first order, second order, etc., depending on whether they are perceived next to the source or second from the source, etc. Given the distance between the narrow, equally spaced slits, corresponding wave-lengths may be computed from the deviations of the various colored beams. For light incident normally (Fig. 1),

$$n\lambda = d \sin \theta,$$

in which n represents the order of the spectrum, λ the wave-length, d the distance between successive slits, and θ the angle. Wave-lengths are usually designated in terms of the micron. One micron equals 0.001 mm. The symbol for the micron is the Greek letter μ.

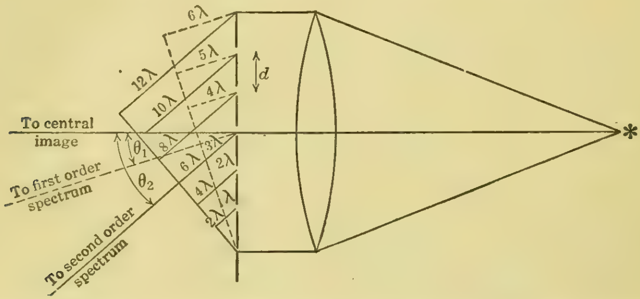


FIG. 1. Diagram to Illustrate Action of Grating in Forming Spectra.

The Prism. — Triangular prisms of glass, quartz, rocksalt and certain other substances are also used to form spectra. Those formed, however, do not follow the simple law of the grating. The deviation angles corresponding to various wave-lengths are usually calibrated by means of the latter.

For wave-length measurements, prisms are secondary to gratings in importance. However, when the intensities of the radiations associated with different wave-lengths are considered, the situation is the reverse. A prism deviates all of the transmitted radiation into a single spectrum, while a grating deviates only a part of the transmitted radiation, usually in unpredictable amounts, into many spectra.

Color Wave-length Relations. — A definite color or hue is associated with each wave-length of visible radiation. In passing from one end of the visible spectrum to the other there can readily be distinguished not only the main divisions of color, such as red, orange, yellow, green, blue and violet, but also, if conditions are satisfactory, several hundred additional colors. The boundaries between the main subdivisions are indefinite, differing with different people. For a rough subdivision the following boundaries may be assumed: 0.78μ — red — 0.63μ — orange —

0.59μ — yellow — 0.55μ — green — 0.49μ — blue — 0.45μ — violet — 0.38μ. The limits of the visible spectrum may be assumed as 0.78μ and 0.38μ.

Infra-red Radiation. — Herschel, in 1800, using a glass prism to show that the radiations in a visible spectrum will affect a thermometer exposed to them, found that the most marked heating effects are obtained outside of the visible spectrum — the only portion then known — in what is now called the infra-red spectrum (Fig. 2). Infra-red radiations are similar in nature to those producing vision, the sole difference being the greater wave-lengths of the infra-red. Many people refer to these radiations as heat rays. This term, however, is a misnomer, since the heating effects produced by them differ only in degree from those produced by the visible spectrum.

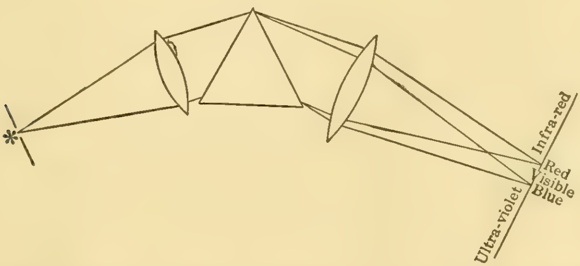


FIG. 2. Diagram Showing Relation of Ultra-violet and Infra-red Radiations with Respect to the Visible in the Spectrum of a Source Formed by a Prism.

The existence of infra-red radiations is readily demonstrated by exposing a radiometer to an incandescent lamp, first directly, and then through a screen containing a dense solution of iodine in carbon bisulphide. This screen has the property of transmitting infra-red radiations and of absorbing visible radiation. The indication of the radiometer corresponding to the heating effects of the radiations incident upon it is seen to be somewhat smaller in the second case. This shows that by far the larger portion of the radiation from the lamp lies outside the visible spectrum. Other work shows it to be infra-red.

Ultra-violet Radiation. — Similarly, in the region beyond the blue and the violet, radiations are found which are capable of producing marked effects, particularly of a photographic nature.

The existence of such radiation is readily shown by means of a quartz spectrograph (an instrument particularly adapted for obtaining such spectra) which is pointed at a mercury-in-quartz arc or an iron arc. A piece of ground glass placed in the focal plane will show only a concentrated visible spectrum. If a piece of uranium glass is now substituted for the ground glass, there will appear, in addition to the visible

spectrum, a great many lines in the region beyond the blue edge of the visible spectrum. The radiations which produce them are incapable of producing vision directly; but, when they impinge on certain substances such as uranium glass, they are able to cause those substances to emit other radiations whose waves possess a different frequency and wave-length. The process is known as fluorescence. In this case, the fluorescent radiation is visible. Because of their location in the spectrum, the exciting radiations in this case are called ultra-violet radiations. So far as known, they differ from visible radiations only in that they have shorter wave-lengths.

X-rays and γ-rays. — Recent work has shown that X-rays (or Roentgen rays) differ from those which have just been considered, only in that their wave-lengths are exceptionally short, commonly of the order of a thousandth or a ten-thousandth of those occurring in visible radiation. Crystals interposed in the path of a narrow homogeneous beam of X-rays will produce diffraction effects similar to those produced by gratings on ordinary light. In fact, crystals are diffraction gratings with three dimensions instead of two. The grating space, corresponding to the distance between lines in the ordinary grating, is the distance between atomic planes.

Associated with the disruption of atoms in radioactive processes, there often occur emissions of γ-rays. They are of the same nature as X-rays and possess wave-lengths of the same order of magnitude. It is probable that they are produced by quite similar causes.

Spectrum of Radiation. — In Table I are shown the various known classes of radiation together with the limits as to wave-lengths within which measurements have been made. The velocities of all in free space are identically that of light, viz., 299,860 km./sec. Since the product of frequency of vibration and wave-length gives the velocity of propagation, it is a simple matter to determine the frequencies of vibration in various sources, which will give the limits of radiation specified.

Until recently, certain gaps existed in the table, one between the shortest measured wireless waves and the longest known infra-red waves, and the other between the shortest known ultra-violet waves and the longest known X-rays. Now the former gap has been spanned, and means have been found whereby certain radiations may be both produced and measured by the methods of wireless telegraphy and of infra-red measurements.

Similar progress has resulted in the narrowing of the other gap. It is believed that spectral images, or lines, as they are usually called, which have the characteristic X-ray origin, have already been detected

and measured by the methods characteristic of ultra-violet measurements. In fact, the radiations at the short wave-length limit of the ultra-violet spectrum of the higher elements belong to this class.

TABLE I

SPECTRUM OF RADIATION

Class	Wave-length Limits
Wireless telegraphy	25 km.
Hertzian waves	0.2 mm.
Infra-red rays	0.3 mm. – 0.78μ
Visible rays	0.78μ – 0.38μ
Ultra-violet rays	0.38μ – 0.032μ
X-rays and γ-rays	12.00 Å – 0.07 Å

0.001 km. = 1 m. = 10^3 mm. = $10^6\ \mu$ = 10^{10} Å

The region dealt with in this work is that which is included under the infra-red, the visible, and the ultra-violet.

Types of Spectra. — Two types of spectra have already been noted. In one, radiation of only certain definite wave-lengths is present. Spectra of this type, of which that due to the mercury arc is illustrative, are known as bright-lined spectra. In the second type, radiations of all wave-lengths throughout the measurable spectrum are present. Spectra of this type, of which that due to an ordinary incandescent lamp filament is illustrative, are known as continuous spectra.

There are three other types of spectra — the dark-lined, the bright-banded and the dark-banded. Typical of dark-lined spectra is that due to the sun, which is continuous save for a great many dark lines which cross it at irregular intervals. The significance of these dark lines will be discussed in the study of the sun's radiation. Bright-banded spectra, such as occur in the light from the firefly and phosphorescent and luminescent glows, possess spectra which are continuous for certain ranges of wave-lengths only. Although really belonging to the bright-lined group, spectra with groups of closely related bright lines, which appear as bright bands in spectrometers having low resolving power, are also commonly called bright-banded spectra. Dark-banded spectra are continuous spectra streaked with dark bands, that represent regions for which there is little or no radiation present. The spectrum of light from an incandescent lamp which has passed through a colored glass is a good illustration of this class.

Measurement of Effects Produced by Radiation

Effects Produced by Radiation. — Mechanically, light beams exert pressures. The great illustration in nature is the comet's tail, which seems to be due largely to the pressure exerted by the sun's radiation upon the very much attenuated particles constituting the comet. A curious consequence is that the tail of a comet, while following the comet naturally during the approach toward the sun, gradually swings to one side as the perihelion is approached and passed, and finally leads the comet into outer space. This peculiar behavior results from the fact that the tail is a grand collection of minute particles leaving the head of the comet under the influence chiefly of radiation pressure. The material in the tail is changing constantly. Because these particles move faster than the comet, the " tail ahead " feature naturally results.

Thermally, radiation is capable of raising the temperature of things exposed to it. Illustrations of this are obvious. Chemically, there exist the processes of photography, fading of dyes and paints, hardening of certain substances by sunlight, etc. Electrically, there are the resistance changes which occur when selenium is exposed to radiation, the ionization which occurs in the surrounding atmosphere when certain metals are exposed to certain radiations of short wave-length, and the phenomenon of the upper atmosphere known as the Aurora Borealis. Visually, there is the effect on the eye. Still another effect is fluorescence, the phenomenon described above in demonstrating the existence of ultra-violet radiation. In measuring radiation, these effects and combinations of them are used.

Measurement of Radiant Energy. — Measurements of radiant energy are usually based on heating effects produced by the radiation. The instruments most commonly used are the thermocouple, the bolometer and the radiometer. In the thermocouple, the heat developed produces a thermal electromotive force; in the bolometer it produces a change in the resistance of a very thin blackened strip of platinum; in the radiometer, it produces an increased gaseous pressure in the neighborhood of an absorbing vane in a partial vacuum, which results in a torque on a suspended system. The indications of these instruments depend upon the rate at which radiant energy is received. Only when their indications are integrated over an interval of time are energy measurements really obtained.

Spectral Energy Curve. — By plotting against wave-length the indications of a radiometer or some other so-called energy-measuring instrument, exposed successively to different small elements of the spectrum of a source as produced by a prism, a curve is obtained which

shows the relative heating effects for the various wave-lengths of radiation from that source. Such a curve is spoken of as a spectral energy curve.

Thus curve *a* of Fig. 3 is a spectral energy curve showing the relative heating effects associated with different wave-lengths for tungsten at about 2200° K. (a temperature about 250° less than that occurring in ordinary vacuum tungsten lamps). It shows, for instance, that the maximum heating effect for a given short interval of wave-lengths for tungsten at that temperature is located at 1.2μ and that there such

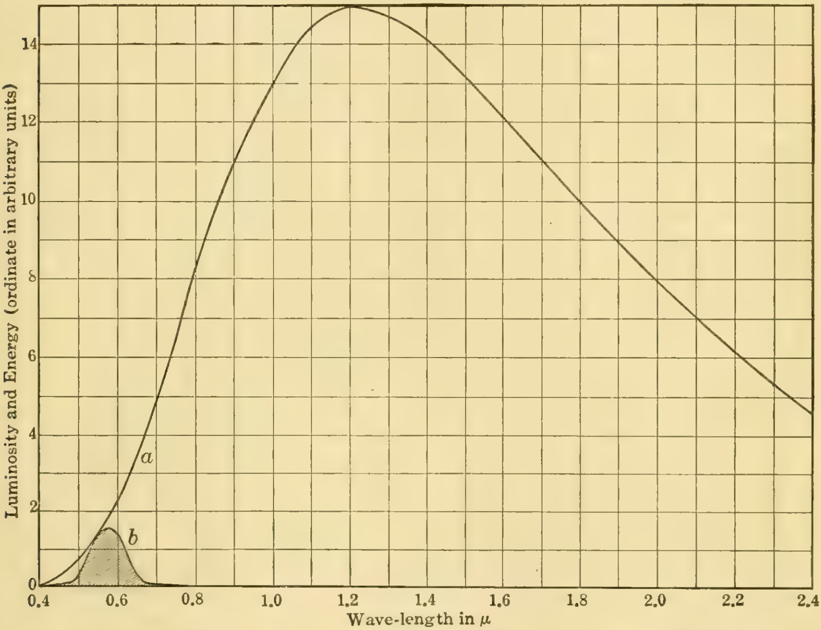


FIG. 3. Spectral Energy Curve (*a*) and Spectral Luminosity Curve (*b*) of a Tungsten Filament at about 2200° K.

That portion of the area enclosed under curve "*a*" which is beyond the limits of this diagram is equivalent to about 25 squares.

effects are about twice those experienced by a similar interval at the red end of the visible spectrum (0.78μ), and perhaps a hundred times more than is to be expected at the blue end (0.38μ).

If the indications of the heat-measuring instrument are represented by slender rectangular areas with widths on the plot proportional to the short interval of wave-lengths impinging on the instrument, it follows that the total heating effect, taking account of all wave-lengths, is represented by the area inclosed between the spectral energy curve

and the wave-length axis, since this area is nothing more or less than the sum of all the elementary, slender rectangles, which touch but do not overlap. From the standpoint of heating effects, the infra-red portion of the spectrum in this case constitutes by far the greater part of the whole. The ultra-violet portion is almost negligible. Within the visible range, only about 4 or 5 per cent of the energy is radiated.

Spectral Luminosity Curve. — If the eye is used in place of the radiometer to evaluate the radiation from a source, a different spectral evaluation curve will be obtained. Since the eye cannot be calibrated to give an absolute determination of a visual effect, but can determine equality or lack of equality between two separate visual effects simultaneously obtained, something more than a simple substitution of the eye for the radiometer is necessary in the experimental procedure. The instrument used for this type of work is the spectrophotometer (see page 225). With it, convenient comparisons may be made between the visual effects from various portions of the spectrum of an analyzed source and those from some constant standard source, the visual effects from which may be varied as desired by mechanical subdivision.

The evaluation of the radiation from tungsten at 2200° K. by the eye will give some such curve as *b*, Fig. 3. It is called the spectral luminosity curve of the source. It shows that at certain wave-lengths the visual effect or luminosity is much greater than at others, the maximum effect being in the neighborhood of 0.58μ. Toward either end of the visible spectrum the luminosity decreases. Reasoning similar to that applied to the spectral energy curve shows that the area under the spectral luminosity curve represents the total visual effect.

On the assumption that the eye as a machine is 100 per cent efficient, making full use of the incident radiation only at that wave-length at which curves *a* and *b* are tangent, and that at other wave-lengths the eye's efficiency is relatively reduced, it must be concluded that the eye is not only incapable of responding at all to about 95 per cent of the radiation from the filament, but also that, considering the reduced efficiency in various parts, its overall efficiency for this source is of the order of 1 per cent (the ratio of the area enclosed under *b* to that under *a*) of the maximum possible value.

The blame for this poor efficiency may be thrust upon the source by saying that, from the visual standpoint, its radiation is inefficient, or that the efficiency of a lamp is only 1 or 2 per cent of the theoretically highest possible value.

Each source has a characteristic spectral luminosity curve; further, the curve for any particular source changes with temperature. A tungsten filament at 1800° K. has a spectral luminosity curve which

differs from that at 2200° K., shown in Fig. 3, by being relatively deficient in the shorter wave-lengths, the dividing line being in the region of 0.55μ. This change corresponds to the reddening which is noticeable on lowering the temperature of the tungsten filament. If the temperature is raised, an opposite change is found to correspond to the whitening of the source.[7] Similar changes take place in the spectral energy curve.

Employing a similar method, spectral photographic-action curves, and, indeed, spectral curves for any effect due to radiation may be obtained and analyzed.

Contrasts in Heating, Visual and Photographic Effects. — How differently a radiometer, an eye and a photographic plate (through a glass lens) weight the radiation from a source is shown by the spectral energy, the spectral luminosity and the spectral photographic-action curves of the source. A particular comparison of weights may be made from Fig. 4, in which spectral distribution curves are given for a high-efficiency tungsten lamp and a blue-sky source for the visible and a small portion of the ultra-violet regions. For ease of comparison, a condition of equal total illumination has been selected for plotting, i.e., the scales have been so chosen that the areas enclosed beneath the two spectral luminosities are equal. The difference in the total weights assigned by the radiometer and the photographic plate is readily observed. Those familiar with photography will perceive that this is consistent with the greater photographic efficiencies of blue-sky illuminations actually experienced.

Definitions of Light. — It is necessary to define the term "light" specifically. Several usages have been recognized, but for this discussion light will be considered as a quantity which stands in the same relation to the visual effects of radiation that radiant energy does to the heating effects. Thus the potential heating effects of the radiation from a source, when summed up over a period of time, give the energy radiated during that interval. Similarly, the potential visual effects of the same radiation, summed up, give the light radiated during that interval.

Visibility of Radiation. — Though the spectral energy and spectral luminosity curves differ from source to source, the visibility function which connects them does not. This function shows the relative efficiency of the eye in responding to radiations of various wave-lengths. It is a property of the eye — more strictly, of the seeing mechanism — and is, therefore, the same whatever the source used in its measurement. Plotted as a function of wave-length, it forms the visibility curve. The visibility curves of individuals having normal vision differ slightly, and for practical purposes an average curve is used.

The absolute value of the visibility at any wave-length is the ratio of the visual effect to the heating effect of the radiation at that wave-length, and is expressed in lumens per watt. For example, at 0.556μ the visibility of radiation is 670 lumens/watt. This means that a

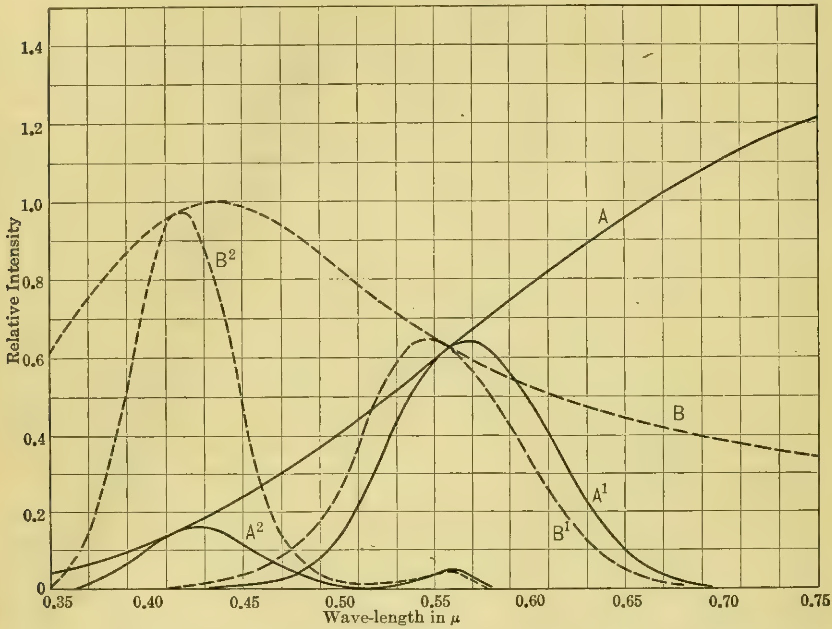


FIG. 4. A Diagram Showing How Differently the Eye, an Ordinary Photographic Plate (through a glass lens), and a Radiometer, Weight the Radiations from a Blue Sky, and from a High-efficiency, Gas-filled Tungsten Lamp. The curves represent distributions for equal illuminations.

A-— the spectral energy distribution of the lamp.
B-— the spectral energy distribution of the blue sky.
A^1 — the spectral luminosity distribution of the lamp.
B^1 — the spectral luminosity distribution of the blue sky.
A^2 — the spectral photographic action distribution of the lamp.
B^2 — the spectral photographic action distribution of the blue sky.

radiant flux of 1 watt at 0.556μ is measured visually as 670 lumens. If the 670 lumens are regarded as the output of the eye for an input of 1 watt of radiant flux, this visibility ratio is seen to represent an efficiency of radiation associated with the wave-length 0.556μ.

From curves A and A' or curves B and B', Fig. 4, a curve may be computed which will show relative visibilities. It will be readily seen that a maximum relative visibility of unity is obtained in the yellow-green at 0.556μ, and that in passing to shorter or longer wave-lengths

the relative visibilities gradually decrease to zero values at the violet and the red ends of the spectrum. Though the ordinates of curves A' and B', Fig. 4, are too small to show on the plot beyond 0.70μ, visibilities have been measured out as far as 0.76μ. At 0.60μ the relative visibility is about 63 per cent; at 0.65μ, about 11 per cent. Values of the relative visibility instead of the values in absolute units are often plotted as functions of wave-length.

Visibilities in absolute units are obtained by multiplying relative visibilities by 670 lumens/watt, the absolute value at the maximum (this quantity is the inverse of the mechanical equivalent of light, 0.00150 watts/lumen). Thus, at 0.556μ, 0.60μ and 0.65μ, the absolute visibilities are 670 lumens/watt, 420 lumens/watt and 74 lumens/watt. As with the maximum visibility, the visibilities 420 lumens/watt and 74 lumens/watt may be looked upon as the efficiencies of the radiations associated with wave-lengths 0.60μ and 0.65μ. The visibility curve as a whole when in absolute units may be regarded as a curve showing the spectral luminous efficiency of radiation.

The contrast of the maximum spectral efficiency of 670 lumens/watt with the average overall efficiency (including ultra-violet and infra-red) of about 6 lumens/watt for a tungsten filament at about 2200° K. is consistent with the conclusion reached in connection with Fig. 3, that the overall efficiency of that radiation in producing visual effects is roughly 1 per cent of the maximum possible efficiency.

A visibility curve furnishes the means for obtaining a spectral luminosity curve when the corresponding spectral energy curve is once known. To obtain the spectral luminosity curve in such a case, the procedure consists in plotting, as a function of wave-length, the products of visibilities and corresponding spectral energy ordinates.

Lamp Efficiency. — Lamp efficiency, like other efficiencies, represents the ratio of an output to an input. In this case it is customary to measure these two quantities in different units. The input of a light source is commonly measured in watts, the output in lumens, and the efficiency, therefore, in lumens/watt. Thus, the operating efficiencies of the ordinary 110-volt vacuum tungsten lamps range around 10 lumens/watt.

In some instances, as in preceding sections, the efficiency, not of a source, but of the radiation from a source called luminous efficiency, is spoken of, just as though the radiant flux from the source, measurable in watts, were the input of the eye as a machine and luminous flux, measurable in lumens, were the output. In ordinary vacuum incandescent lamps, the rate of supply of energy, except for some small losses, is equal to the rate of radiation of energy. In such cases, the lamp efficiency

of the source, though lower, is practically equal to the luminous efficiency of its radiation. The case is different in gas-filled incandescent lamps, where the rates of supply and of radiation of energy differ considerably on account of the conduction of heat away from the filament by the gas in the lamp. In such cases the efficiency of the source is noticeably lower than that of the radiation. It is generally easy to determine, from the context, which of these quantities is referred to.

Visibility and luminous efficiency are quantities of the same nature. Both are expressed in lumens/watt. Usage, however, has limited the use of luminous efficiency to the ratio of total luminous output to total radiant flux, including therein the infra-red and the ultra-violet regions; and the use of visibility to the similar ratio for approximately monochromatic radiation. Unlike the luminous efficiency, the visibility associated with a particular wave-length is the same under normal conditions, whatever the actual source considered.

It is interesting to consider certain values of efficiency. The highest attainable value, using an ideal source which radiates energy only in the region of maximum visibility, is 670 lumens/watt. The highest possible white-light efficiency from an imaginary source which would radiate in the visible much as does the sun but which would have neither infra-red nor ultra-violet radiation, would be about 250 lumens/watt. The highest possible efficiency for black-body radiation, a type which will be discussed later, is about 90 or 95 lumens/watt. Contrast these with the efficiencies of 10 to 30 lumens/watt, which are obtained with the most efficient light sources, and it is evident that a great gain is possible in commercial light production.

Color

Color of a Light Source. — The color of a light source refers to its appearance when viewed directly or the appearance of a truly white surface illuminated by it. It depends primarily on the spectral distribution of the luminous flux. This is true both of strongly colored sources, such as flames burning salts and mercury-vapor lamps, which have bright-line or bright-band spectra, and of tungsten and carbon lamps, which have continuous spectra.

The apparent color of a source may be considerably modified by an intervening medium. A most conspicuous example is the color change which the sun seems to undergo in passing from zenith to horizon. The cause for this, as well as the origin of the sky as a light source, is related to the body color of the atmosphere. By body color is meant that

color which an object possesses on account of its selective action in absorbing, scattering and transmitting the penetrating radiations, so that certain wave-lengths are more copiously reflected or transmitted than others. In the atmosphere the agents producing the selective effects are dust particles, small water drops, and the molecules of the air itself. When the sun is high, the radiation which reaches the earth penetrates only a relatively thin layer of atmosphere. Though radiations of all wave-lengths are scattered, the effect is by far the most noticeable for the short, or blue, wave-lengths. The apparent color of the sun, though not greatly changed, is appreciably reddened thereby. The light that has been scattered, being predominantly blue, gives to the medium that scatters it a blue color; hence the blue sky. The agents that scatter selectively also absorb selectively and in this process the blue radiation is much more rapidly eliminated with increased length of paths of light through the atmosphere than the red radiation. Thus the sun and the western skies at sunset are reddish because of some scattering of all wave-lengths and of the practical elimination of the blue by absorption. The gradual change which takes place is well shown in Fig. 5, in which are shown spectral energy curves of the sun's radiation through the atmosphere, for various azimuths. The passage from the zenith to an altitude of $7\frac{1}{2}°$, for instance, is accompanied by a reduction in luminosity of about 85 per cent in the blue region (0.5μ) and of roughly 50 per cent in the red region (0.65μ).

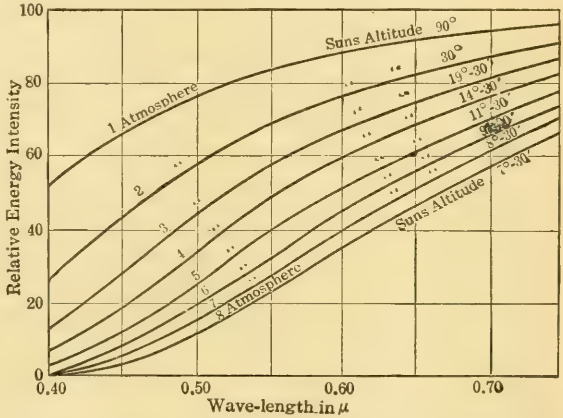


FIG. 5. Spectral Energy Curves of Sunlight at Different Altitudes Showing Effects of Scattering and Absorption by the Atmosphere.

Colors of Material Objects. — The color of a non-luminous material object depends upon the spectral character of the incident light and upon the selective action of the object on that radiation. That the character of the source is important is shown by the contrast which the mercury arc and the incandescent lamp cause in the appearance of human beings upon whom their light falls. That the selective actions

of objects are equally important may be shown by a simple demonstration. Several narrow strips of highly colored papers mounted end to end on a dark cardboard, a diffraction grating, and a source of light yielding an intense narrow directed beam are required. In a darkened room, in the narrow beam, the colored strips of paper will serve as secondary sources. Their spectra as seen through the grating will show just how their colors are linked up with their selective actions. The spectrum of a white strip will show all colors; that of a red strip, for example, will perhaps also show all colors, but with their relative brightness, in comparison with that for the white, decreasing rapidly toward the violet. As a result of the selective action, the center of the spectrum of the red strip appears much nearer the red edge. Similar characteristics will be noted for the spectra of the other colored strips.

When the appearance of an object is due to selective action taking place within the medium, the color of the object is said to be a body color. Snow, steam, paint pigments, and the earth's atmosphere are illustrations. When the appearance is due to the selective reflection which takes place at the surface, as is the case with most metals, the color of the object is said to be a surface color. Gold possesses its distinctive orange-yellow color because of its copious selective reflection of light of certain wave-lengths.

Relation Between the Color of a Body as a Light Source and as a Material Object. — The color of a source emitting radiations in consequence of a high temperature is closely tied up with its color as a body. The color of an incandescent lamp source depends not only on the temperature of its filament, but also on its selective action in emitting radiations of various wave-lengths. This latter characteristic for such a source is directly connected with its selective absorbing action for radiation that may fall upon it; that is, directly connected with one of the factors which determines its color as a body. This viewpoint will be considered further in the section on "Black and Non-black Radiators."

Incandescence and Luminescence

Definitions. — Radiations belonging to the visible and the adjacent ultra-violet and infra-red spectra are divided into two classes, incandescent and luminescent. The distinction between the two types is not entirely definite, though ordinarily but little difficulty is experienced in classifying the radiation in any particular case.

Incandescence, or temperature radiation, as it is often called, is that type of emission in which the radiation is due to, and stands in a definite

quantitative relation to the temperature of the source. It is well illustrated by the emission from an ordinary incandescent lamp filament or any other heated solid. Radiation of this type gives usually, if not always, a continuous spectrum in which all wave-lengths are present.

Luminescence is that type of emission in which the radiation is not related in a strict sense to the temperature of the source. It is well illustrated by the radiation from mercury vapor in an ordinary mercury-vapor arc or by the radiation which comes from the arc proper (not from the electrodes) of any arc lamp. To illustrate, when mercury vapor is heated in an oven to the temperature which occurs in the mercury-vapor arc, very little, if even a trace, of the arc radiation is observable. The fundamental cause of radiation in the arc source is something other than temperature. The spectra of the typical luminescent sources are quite distinct, being of the bright-line or bright-band types.

One reason for the difficulty experienced in some cases in differentiating between the two types of radiation probably is the occurrence, in many instances, of both types in varying proportion. The present lack of knowledge of processes involved in various sources is probably another reason for this difficulty.

Electrical Structure of Matter. — A study of the ultimate sources of radiation is intimately connected with a study of atomic structure. Many facts profoundly affecting our conceptions of structure have been discovered during the past twenty or twenty-five years. New discoveries are gradually being made. Theories of atomic structure are being formed, revamped and discarded. It is not safe to predict what the ultimate concept will be like. However, throughout all changes in theory, certain results and considerations have won well-nigh universal acceptance.

The great advance in the study of the nature of matter dates back to 1859 when Plücker noticed the phosphorescent patches produced on the surface of highly exhausted glass bulbs through which very high-voltage electric discharges were passing. Subsequent work indicated that the phosphorescence was due to rays of some kind originating at the cathode. They were called cathode rays. Projected in straight lines from the cathode, they cast shadows of opaque obstacles in their path and are capable of producing fluorescence in various interposed materials, of being deflected by electrostatic as well as magnetic fields, and of charging negatively any conductor upon which they impinge. It was not until 1897, however, that Sir J. J. Thomson demonstrated at the Cavendish Laboratory at Cambridge University that these cathode rays are " charges of negative electricity carried by particles of matter." These particles are now known as electrons.

Thomson obtained, moreover, a value for e/m, the ratio of the charge of the electron to its mass (1.766×10^7 electromagnetic units of charge per gram, according to more recent determinations) which indicated that the mass of the negatively charged electron is about 1/1850 of that of the hydrogen atom as determined by electrolysis. He found that changing the material of the cathode did not alter the value of e/m, indicating that the electrons, wherever found, are alike. Later still, he also showed that the whole of the mass of the electron could be ascribed to the inertia of the electrostatic field connected with its electric charge.

This view has received experimental confirmation and is now universally accepted. The radius of the electron on Thomson's supposition is of the order of 10^{-13} cm., roughly 1/100,000 of the distance between atom centers in the most compact solids.

Results obtained more recently by Rutherford, Sir J. J. Thomson's successor at the Cavendish Laboratory, and others seem to indicate that there is a positive elementary charge or proton whose mass, however, is much greater than that of the electron. It is generally believed that the electrical charge of the proton is numerically equal to that of the electron though opposite in sign. The theory which, applied to the electron, gave a radius of 10^{-13} cm. gives in this instance a much smaller value. In fact, the radii are taken as inversely proportional to their masses. Assuming a hydrogen atom to be made up of one proton and one electron, as is ordinarily done, this would mean a radius of the order of 10^{-16} cm. for the proton. Such dimensions seem to be in accord with, and in fact demanded by, Rutherford's work. It seems that all mass whatsoever is electromagnetic in nature.

The atoms of all substances are believed to be made up of combinations of protons and of electrons sufficient in number to render the whole electrically neutral, and so arranged as to make more or less stable units. In some instances, e.g., uranium, radium, thorium, the stability is relatively not great, and the atoms spontaneously decompose.

The most commonly employed concept of the hydrogen atom consists of an electron revolving in an orbit about a proton. In the case of helium, the picture consists of a nucleus of four protons and two electrons about which two electrons move in relatively distant orbits. In the case of the other atoms, the pictures are similar, though in each case the excess of protons over electrons in the nucleus is different from that for every other atom. In fact, it is the nuclear charge or the atomic number (the nuclear charge divided by the charge of a single proton) which is believed to determine the nature of the atom, i.e., whether it is oxygen, or chlorine, or something else. Whether the electrons out-

side a nucleus are in orbital motion or are relatively stationary is a point on which people interested in radiating properties differ with those interested in chemical properties.

Metallic Conduction. — The electron theory, as it is called, has entered intimately into the explanation of physical phenomena. The passage of a current through a metal wire, for instance, may be explained thus: When atoms are closely packed, as in solids or liquids, it may be assumed to happen often, as in metals, that the interatomic forces are such as to result in the loose binding of certain of the electrons of the atoms. As a result of thermal agitation they move about among the atoms more or less freely. Their velocities will vary greatly in magnitude and direction, following generally the same distribution that results from the thermal agitation of the molecules of a gas. One difference is to be expected, however. Gaseous molecules ordinarily maintain their identities intact as they impact and rebound; but often the impact of a free negative electron will result in its loss of freedom. Equilibrium conditions, however, will be maintained through the freeing of other electrons in the same or neighboring atoms.

The application of an electromotive force to such a wire will cause a drift of the free electrons contained in it and result in an electrical current. Electrical resistance is explained as the hindrance which the larger atomic masses and positive residues of atoms offer to the drift. A positive residue consists of the remainder of an atom after the removal of one or more electrons. A considerable number of the impacts, through recombination, result in the elimination of free electrons. Other negative electrons becoming free, however, must be given the directed velocity in order to take up the drift required for the current. This requires the constant expenditure of work and results in the heating which is ordinarily said to be due to electrical resistance.

Differences in resistivity are accounted for by the concentration of the free electrons, their average velocities and their average paths between impacts with atoms. On this basis insulators are merely poor conductors because they have very few free electrons.

The foregoing theory employing free electrons satisfactorily explains many phenomena, including that of the origin of radiation in heated solids. Considered by itself, however, it fails in the explanation of certain other phenomena. Other theories have been advanced which succeed in places where the foregoing fails, but none generally satisfactory has yet been developed.

Gaseous Conduction. — Gases and vapors, including metallic vapors, except at very high temperatures, in states of equilibrium ordinarily have their molecules so far removed from one another, and the inter-

molecular forces so weak, that electrons ordinarily are no longer freed by thermal agitation. In this condition of no free electrons, a gas or vapor is a non-conductor. The application of strong electric fields and of various other means may be used, however, to ionize a gas or vapor. The process consists in the tearing away of one or more electrons from various atoms or molecules. In case such ionization occurs in an electric field, the electrons and the positive residues of the atoms or molecules that are formed will then move in opposite directions. Some of the electrons and some of the positive residues may associate with themselves un-ionized molecules and perhaps also other electrons and positive residues, forming larger electrically charged units, usually referred to as ions. (Strictly speaking, the ion includes also the electron and particularly the positive residue.) Whether in the presence of an external electric field or not, many of the positive and negative ions will recombine to form aggregations that are neutral or more nearly so. If neutral, the component parts will separate into the original molecules.

The movement of the electrically charged ions — the positive toward a cathode, the negative toward an anode — constitutes a current through the gas or vapor. In contrast with metallic conduction, there is here a close resemblance to electrolytic conduction.

The Ultimate Radiators. — The processes of ionizing atoms and molecules and of recombining of the component parts are intimately connected with the radiation of energy. To the best of our present knowledge, those component parts taken in pairs or in groups are the ultimate radiators. The mechanics involved in the radiation process, whereby they are able to snap off, so to speak, a portion of the energy from the supply which has been stored up about them, is not only uncertain but beyond the scope of this course. Certain of the factors involved will be discussed to some extent, however.

The Energy Emitted by the Ultimate Radiators. — The energy of formation of an atom in comparison with the amounts of energy it absorbs or liberates in ordinary chemical reactions is enormous. It is believed to be stored up for the most part in the space (the interpenetrating ether is stressed, according to those who believe in its existence) within and between the component parts, largely as electrostatic potential energy.

The separation of an electron from an atom, together with the probable readjustment in the positive residue — that is, the ionization of an atom — requires the performance of work. The energy contributed by the outside agent in this process will appear as electrostatic energy in the intervening space. It represents quantitatively the energy which is radiated when recombination of an electron with the positive

residue takes place at some later time. If perchance the frequency of the radiation is within certain limits, vision may result. When recombination is complete, the total amount of energy radiated is equal to the energy of ionization. Atomic systems are conservative.

Much radiation takes place from atoms only partially ionized. The impacts of electrons or ions driven by electric forces upon neutral atoms, while often not sufficiently severe to ionize them completely, may, however, be severe enough to produce partial ionization — that is, an electron forming a part of an atomic structure may be shifted from its normal stable position to another position of less stability. The energy contributed by the ionizing agent, manifested by a decrease in its kinetic energy, will be stored up as electrostatic energy in the neutral atom. With the return of the atom to its original state, this same amount of energy will be radiated into space. As in the case of complete ionization, the frequency may be such that vision will result.

In case of partial ionization, the radiation process will ordinarily follow the partial ionization at once or nearly so. In case ionization is complete, a considerable interval of time may elapse; and recombination may take place between component parts from atoms that were originally quite independent.

Values of the order of 0.001 sec. and even 0.01 sec. have been obtained for the interval between a stoppage in the production of ions in a mercury arc and the time at which the rate of recombination had become so faint as to escape visual detection. Short as these intervals are, they are much longer than the time usually required for an atom partially ionized to return to its normal state, for which values of the order of 10^{-6} sec. have been obtained. Regardless of the time interval, the process of radiation is the same. In each instance, electrostatic energy, associated with the separation, partial or complete, of an electron and the positive residue of an atom, is the energy radiated.

A simple experiment may be performed to illustrate that radiation occurs during the return of the radiating material to its normal equilibrium condition rather than during the interval in which energy is being supplied to disturb that condition. A small high-tension discharge between two terminals in a commercial argon atmosphere, such as occurs in ordinary gas-filled lamps in which the terminals are not heated to incandescence, will cause a flame-like discharge from which a bluish-white fog issues and is carried upward by convection currents. A sudden stoppage of the discharge results in the immediate dying out of the flame and stoppage of the fog formation. Now, if the test is made in a darkened room, the fog formation will continue luminous, though gradually and rapidly decreasing in brightness. Intervals of

the order of 8 or 10 seconds previous to the complete dying out are easily obtained. The great length of time for the full recovery is probably associated with some changes other than simple ionization. However, it is evident that the radiation occurs at recovery.

Radiating and Ionizing Potentials. — There are significant data relating to sodium which illustrate the two types of radiation following partial and complete ionization. It has been found that atoms of its vapor, when bombarded by electrons that have speeds resulting from a passage through potential drops of 2.091 volts and 2.093 volts (2.12 volts as measured), yield the characteristic orange-colored spectral lines at 0.5898μ and 0.5892μ. In this condition the sodium vapor is not ionized and will not support gaseous conduction. When, however, the potential drop is changed to 5.111 volts (5.13 volts as measured) ionization takes place, the vapor supports gaseous conduction, and many more lines, including one in the ultra-violet at 0.2413μ, are found in the spectrum. The lines at 0.5898μ and 0.5892μ follow partial ionization; the one at 0.2413μ follows complete ionization. The potential drops required for these effects are called respectively radiating and ionizing potentials. Many other radiating potentials for sodium, corresponding to some of its other spectral lines, are believed to exist, but thus far experimental technique has not permitted of the proof.

The Supplying of Energy to the Ultimate Radiators in Luminescence. — In the further discussion, a distinction will be drawn between luminescence and incandescence. Certain distinguishing features seem to characterize the two methods; though, in each instance, before radiation may take place it is necessary that energy be contributed to the radiating systems to bring about the separation of the component parts of the ultimate radiators.

In the luminescent vapor of a mercury-arc lamp in operation, electrons and positive residues of atoms are found in abundance. Under the influence of the applied electric field, the electrons move toward the anode, the positive residues in the opposite direction. Owing to the constant acceleration supplied by the field, their velocities attain such values that many neutral atoms on which they impact are ionized. Following such an impact, there will be two or more additional ions subject to the electric field. They may also serve through impacts to produce other ions. Along with this process, recombinations will occur, and a steady state finally will be reached in which the rate of ionization is equal to the rate of recombination. From measurements on the ionizing potential of mercury, it appears that the kinetic energy which the electric field must contribute to an electron in order that it may ionize a neutral atom is nearly three hundred times as great as the

average kinetic energy possessed by the neutral molecules of the vapor at 0° C. Expressed otherwise, the kinetic energy which a negative electron must have in order to ionize a mercury atom is equal to the average kinetic energy which the atoms themselves would normally have were they at a temperature of about 80,000° K. The inability of mere thermal impacts at ordinary temperatures to produce ions and the need of electrical means are evident. In accord with this conclusion, attempts to obtain luminescent radiations from mercury vapor, argon, nitrogen and hydrogen through *heating* the gases or vapors to a temperature of 3200° K. gave negative results. It is to be emphasized that originally the energy which is radiated is supplied electrically, and that in magnitude it is huge in comparison with the energy associated with ordinary thermal agitation of the molecules.

The sources of the energy of ionization in the sodium flame, in the fluorescence which may be seen when uranium glass is exposed to the ultra-violet radiation from a quartz-mercury arc, and in many other cases of luminescence, can be traced in a similar manner. Obviously in the cases specified the energy supply is chemical or radiational. In line with the tendency to explain chemical forces and radiation on an electrical basis, these sources may be considered as truly electrical, as is the mercury-vapor arc.

One general characteristic has been emphasized in the luminescence of the mercury vapor. It is the fact that the temperature of the vapor has little or no effect on the separation of the parts of the ultimate radiators or on the energy which they radiate. This is probably equally true of all cases that are strictly luminescent.

The Supplying of Energy to the Ultimate Radiators in Incandescence. — In the case of an incandescent lamp filament electrically heated, the original source of the energy is the electric current. The method whereby the resistance of the filament operates to make it manifest as heat has already been described. Most of the heat thus developed in such a filament is transmitted by radiation and conduction from the interior to the surface layers from which it is radiated into space.

As in luminescence, the ultimate radiators in incandescence are probably (1) pairs of free electrons and positive residues of atoms recombining to form neutral atoms or (2) partially ionized neutral atoms readjusting themselves to their normal stable conditions. In both types of radiation the agents creating the ultimate radiators are chiefly electrons. In luminescence these electrons have velocities which are directly dependent upon the electric field in which they are located and not upon the temperature of the surrounding gas or vapor. In incandescence the reverse is true. Within metals, as has been noted, atoms

are ionized with ease. Thermal impacts serve not only for the formation of free electrons but also for the distribution of their velocities. Thermionic emission experiments seem to show that their velocities vary in direction and magnitude just as though they were the molecules of a perfect gas, with kinetic energies on the average equal to those for any perfect gas at the same temperature. If the frequency of radiation and the energy radiated depend on the severity of the impacts resulting in partial or complete ionization and in recombination, the radiation from a large group of radiators must depend on the temperature of the free electrons; that is, the temperature of the solid. This dependency upon the temperature in incandescence stands in striking contrast to the dependency on the electric field in luminescence.

Formation of Bright-line and Continuous Spectra. — The source of the radiation in the mercury-vapor lamp seems bound up with the motion of an electron or several of them with respect to the remainder of an atom. In case such atomic sources are not otherwise disturbed, radiations consisting only of certain definite frequencies naturally result. Freedom from these extra disturbances might be expected where the ultimate sources are separated widely from one another and not affected by neighboring atoms, as in a gas. In accord with this, the spectra of ordinary arc sources are of the bright-line type. Usually, if not always, such spectra are independent of the temperature of the source and are, therefore, ascribed to luminescence.

The ultimate sources of radiation in an incandescent solid, unlike those of a gas, are greatly subject to the effect of neighboring atoms. Moreover, the severity of the impacts, resulting in recombination of free electrons and atomic residues, varies widely in accordance with the distribution law for the velocities of the atoms and the free electrons. A natural consequence is a great variation in frequency for the different ultimate sources, with, however, a tendency to group about some particular frequency as the most common. A continuous spectrum results.

In an electric discharge through a gas under a low pressure, the spectral lines, as stated, are for the most part sharp and practically limited to single frequencies. Increasing the pressure and bringing the ultimate sources close to neighboring atoms and their disturbing influences tend toward less sharpness in spectral lines and toward greater ranges of frequencies on either side of the frequencies characterizing the undisturbed source. Gradual increases in the pressures to which gases are subjected tend gradually toward the production of continuous spectra like that due to highly heated liquids and solids. From this point of view, temperature radiation and luminescence represent two extremes of fundamentally the same type of radiation.

Too much emphasis must not be placed on this apparent connection. For instance, though the radiation from the firefly is apparently continuous throughout the visible spectrum, it certainly is not due to temperature, to any noticeable extent — at any rate not to the extent that one would be led to expect by considering pure incandescence and pure luminescence as extremes of the same type of radiation, and all other radiations, as mixtures of these extremes.

PROBLEMS ON PHYSICS OF LIGHT PRODUCTION

1. Find angular deviations of the edges of the visible radiation in first-order spectrum for a grating having 4000 lines per cm.

2. Assume, as is customary, 3×10^{10} cm. per sec. to be the velocity of light, and compute the frequencies in sources of radiation which will give the various wavelength limits of Table I.

3. Compute the frequency for a 450-meter radio wave, compare with the audio-frequency of Middle C, and state the number of waves of one affected by the other.

4. Given that the charge carried by an electron is 4.774×10^{-10} e. s. units, the change in the average kinetic energy of a molecule of gas for each degree of change in temperature is 2.058×10^{-16} ergs, and the "effective temperature" of electrons just capable of ionizing mercury vapor is 80,400° K. Compute (1) the amount of kinetic energy that an electron must have in order to ionize a mercury vapor atom on impact and (2) the potential difference (i.e., ionizing potential) through which an electron must pass in order to attain the necessary kinetic energy. One e. s. unit of potential equals 300 volts.

COLLATERAL READING

Physics of Light Production

Campbell, N. R., Modern Electrical Theory (Cambridge University Press, 2nd edition, 1913).

Encyclopaedia Britannica, Incandescence, **13,** 152 (Cambridge University Press, 11th edition, 1910); Electrical Properties of Gases, **6,** 864 (Cambridge University Press, 11th edition, 1910); **31,** 182 (Cambridge University Press, new edition, 1922).

Foote, P. D., and Mohler, F. L., The Origin of Spectra (Chemical Catalog Co., New York, 1922).

Johns Hopkins University Lectures on Illuminating Engineering (The University Press, Baltimore, 1911).

Steinmetz, C. P., Radiation, Light and Illumination (McGraw-Hill Book Co., New York, 1909).

National Research Council, Bulletin No. 10 (April, 1921); No. 14 (July, 1921); No. 30 (March, 1923).

Nela Research Laboratories, Abstract Bulletin No. 1 (Jan., 1913); No. 2 (Jan., 1917); No. 3 (Oct., 1922).

CHAPTER II

LIGHT SOURCES

Black and Non-black Radiators

[A. G. Worthing]

Black Bodies. — Incandescent bodies are conveniently classed as black bodies and non-black bodies. The former essentially represent standards by which all real non-black bodies are judged.

A black object, as ordinarily conceived, is an opaque object that reflects but little of the light that is incident on it. It is a good absorber of light. The black body of physics is the limit in blackness of all black objects. It not only absorbs all visible radiations but also all infra-red and ultra-violet radiations. No completely black substance is known; platinum-black, one of the nearest approaches, has a reflectivity of about 1 per cent.

The closest approach to the ideal is a relatively large cavity at a uniform temperature, with opaque walls having a small opening for observation purposes. Any radiation incident on this black body, through the small opening, will be almost completely absorbed, no matter of what material the walls may be composed. The great difference between its blackness and that of lamp-black, for instance, is quite apparent when the simple comparison test is made.

Non-black Bodies. — All real bodies are non-black bodies. They range from the almost black, platinum-black and lamp-black, by an infinite variety of steps, to freshly polished silver, which absorbs only a few per cent. The exact percentage absorbed depends not only on the nature of the incident radiation, but also on the temperature of the body, the condition of its surface, the angle of incidence, the nature of the surrounding medium, and certain other less important conditions. As a consequence, there are not only the differences of color of ordinary objects, but also the changes of color that any one object undergoes on heating or when lighted from various directions. This complexity is partly responsible for the meagerness of knowledge regarding materials at high temperatures.

Black Bodies versus Non-black Bodies as Radiators. — A generalization of experience states that all bodies in an opaque enclosure of uniform temperature finally attain the temperature of the enclosure.

Granted this, it may be shown that a black body, in addition to being the best absorber of radiation, is also (excluding luminescence) the best emitter of radiation.

In an enclosure of uniform temperature, suppose a black body and an imaginary non-black body of the same size which radiates energy at a greater rate than the black body when at the same temperature. It is evident that in the course of time the non-black body would become cooler than the black body since it could not compensate for this greater rate of emission by absorbing radiation at a greater rate than the black body, for the black body absorbs all radiation incident. Since this would mean an equilibrium state in which there would be a difference in temperature, a condition contrary to experience, it follows that such a non-black body cannot exist. A black body may be defined, therefore, not only as one that possesses a zero reflection-factor for all wave-lengths of radiation, or a 100 per cent absorption-factor for all wave-lengths, but also as one that at any temperature, in consequence of temperature radiation, radiates energy at the greatest possible rate.

Kirchhoff's Law. — Kirchhoff's law expresses the relation that must exist between the power possessed by a body to absorb incident radiation and its power to emit radiation in consequence of temperature. In a qualitative manner its truth is easily demonstrable. A piece of broken crockery with a decorative pattern, heated to incandescence over a gas flame in a dark room, for instance, shows an unmistakable connection between the powers of emission and absorption. The darker portions of the pattern as ordinarily viewed are then noticeably the brighter. Those portions that are good absorbers of light show themselves, when heated, to be good emitters. This effect is not due to a change in the characteristics of the pottery or the painted design, for if the hot pottery is illuminated relatively strongly the different parts of the pattern will reappear with their customary colors and relative brightnesses.

The exact statement of the law may be obtained from an extension of the reasoning of the preceding section. Suppose a piece of cast iron and a black body are placed in an opaque, constant-temperature enclosure maintained at 1600° K. In time these bodies will assume the temperature of the enclosure. At 1600° K., the emission rate for a black body is 37.3 watts per sq. cm. This, therefore, is also the absorption rate as well as the rate of incidence of radiant energy on its surface. Owing to uniformity of conditions in the enclosure, this is also the rate of incidence of radiation on the piece of cast iron. The cast iron, however, will absorb only 29 per cent of this or at a rate of 10.8 watts per sq. cm. Reflection will account for the remainder, namely 26.5

watts per sq. cm. In order that this method of partition of the incident radiation may not disturb the constant temperature equilibrium, the rate at which the cast iron must radiate energy will also be 29 per cent of 37.3 watts per sq. cm. or 10.8 watts per sq. cm. In general terms, for any given temperature, the radiation rate per unit of area for a non-black body, E_n, is equal to the product of the corresponding rate for a black body, E_b, and the total absorptivity (that is, the absorption factor for the entire spectrum) of the non-black body for the black body radiation, a_t. In equation form, Kirchhoff's law is:

$$E_n = a_t E_b.$$

This law is very fundamental. It is the basis of all theoretical deductions regarding incandescence. It states that any body which is a good absorber is also a good radiator and in just the same proportion. Thus, contrasting carbon and tungsten, carbon is a better absorber of radiant energy than tungsten and, therefore, it radiates energy at a greater rate at any definite temperature than does tungsten.

Since all opaque bodies reflect what they do not absorb, good reflectors (that is, poor absorbers) are poor radiators and vice versa.

The fact that certain bodies are good radiators of energy indicates nothing regarding their desirability as light sources. Conclusions as to desirability as light sources from this point of view are not justifiable without further considerations.

Emissivity and Reflectivity. — The ratio E_n/E_b, giving the relative intensities of the radiations from non-black and black bodies at the same temperature, is usually called the total emissivity or total emissive power of the non-black body, e_t. In accord with present conceptions, the term "emissive power," which seems to be going into disuse, is an especially descriptive term. Thus, in the interior of an opaque body having a constant temperature throughout, as may be shown, black-body conditions exist. Radiations in unchanging rates are emitted, reflected and absorbed. Those which are near the surface and in motion toward the surface are acted upon by the surface layers in such manner that only a portion are able to escape into the surrounding space and form the radiation emitted by the opaque body. As a measure of the property or power of the surface layers to let these radiations through, the term "emissive power" seems especially fortunate.

The definition given for total emissivity, in conjunction with the statement of Kirchhoff's law, shows numerical equality between total emissivity and total absorptivity, i.e.,

$$e_t = a_t.$$

Thus, using the results quoted in the preceding section, the total emissivity of cast iron at 1600° K. is 0.29 which means that its rate of radiation of energy per unit surface area is 29 per cent of that for a black body at 1600° K. Since the radiant energy which is not absorbed by a non-black body must be reflected, the total reflectivity of the non-black body is r_t, where

$$r_t = 1 - a_t = 1 - e_t.$$

These values of r_t and a_t, but not e_t, strictly refer to values obtained when the incident radiation has the spectral distribution of black-body radiation having the same temperature as the non-black body in question. Thus, cast iron at 1600° K. absorbs 29 per cent and reflects 71 per cent of the radiation from a black body at 1600° K.; but, if the radiation incident comes from a black body at 3000° K., noticeably different numerical values are realized. Since the emission of radiant energy by cast iron does not depend on incident radiation, the value for the emissivity at 1600° K. is fixed.

Spectral Absorption, Emission and Reflection. — Similar reasoning applied to various monochromatic radiations yields similar results for the radiation at any wave-length. Thus (1) at any specified temperature, a black body radiates energy at a greater rate per unit of area in any limited wave-length region than does any non-black body; (2) at any specified temperature, the rate of radiation of energy per unit of area by a non-black body in any limited wave-length region, $E_{n\lambda}$, is equal to the product of the corresponding rate for a black body E_λ, by the spectral absorption factor of the non-black body a_λ, that is

$$E_{n\lambda} = a_\lambda E_\lambda;$$

and (3)

$$a_\lambda = e_\lambda$$

and

$$r_\lambda = 1 - a_\lambda = 1 - e_\lambda,$$

where e_λ and r_λ are the spectral emissivities and the spectral reflectivities for radiation of wave-length λ. Analogous to total emissivity, spectral emissivity of a substance represents the ratio of the radiation intensity of the substance at a given wave-length to that for a black body. Values for a_λ and r_λ concern incident radiation of wave-length λ and therefore do not depend upon the spectral distribution of the incident radiation as do a_t and r_t. The quantities a_λ, e_λ and r_λ vary with the wave-length, and it is necessary to specify the actual wave-length in any particular case by writing, for instance, $e_{0.7\mu}$, $r_{0.7\mu}$, etc.

Variations with temperature occur also, though they are ordinarily much less pronounced.

Illustrative Data. — Consider curves *a* and *b*, Fig. 6, spectral energy curves of tungsten and black body radiation at 2450° K., approximately the normal operating temperature of the 40-watt vacuum tungsten lamp.

By definition, the ratio of the area under curve *a* to the area under curve *b* is the total emissivity for tungsten at 2450° K. In absolute units, the radiant flux from a black body at 2450° K. is about 205 watts per sq. cm., that from tungsten about 50 watts per sq. cm.,

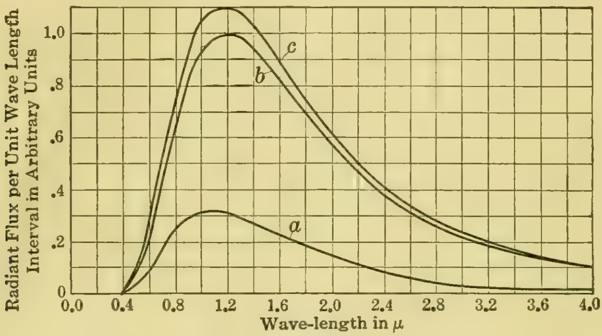


FIG. 6. Spectral Distribution Curves for Radiant Fluxes from
a. Tungsten at 2450° K.
b. Black Body at 2450° K.
c. Black Body at 2500° K.

and the total emissivity of tungsten about 0.27. This ratio changes with temperature. In accord with what has been said, tungsten at 2450° K., when exposed to black-body radiation corresponding to curve *b*, absorbs 27 per cent and reflects 73 per cent.

Spectral emissivities are also illustrated in Fig. 6. The spectral emissivity at 0.8μ for tungsten at 2450° K. is the ratio of the ordinate of curve *a* at 0.8μ to the corresponding ordinate of curve *b*. At this wave-length it is about 0.37; at 1.2μ about 0.31; at 2.0μ about 0.26. In accord with the foregoing, tungsten at 2450° K. will absorb about 37 per cent, 31 per cent and 26 per cent of incident radiation of wave-lengths 0.8μ, 1.2μ and 2.0μ, and will reflect about 63 per cent, 69 per cent and 74 per cent of the incident radiation at the same wave-lengths.

Gray Bodies and Selective Radiating Bodies. — Two types of non-black bodies, gray bodies and selective radiating bodies, are distinguished in practice.

Gray bodies emit radiations which have the same relative spectral

distribution, but not the same intensity as those emitted by black bodies at the same temperature. For any given gray body, the spectral emissivity does not change with wave-length and is equal to the total emissivity. There are probably no real gray bodies. Amorphous carbon, however, represents a fairly close approach.

Selective radiating bodies are those in which the spectral emissivity is not constant for all wave-lengths. In each instance, radiation is relatively more abundant in certain spectral regions than in others, when black-body radiation of the same temperature is taken as standard. Fig. 6 shows tungsten at 2450° K. to be selective with emissivities at 0.6μ, 1.2μ and 2.0μ equal to 0.44, 0.31 and 0.26. This gradual decrease with increase in wave-length also applies to the visible spectrum of tungsten by itself.

Contrasting the selective radiation of tungsten with the practically gray radiation of carbon, it is found that the color of the light from a tungsten filament is somewhat bluer or less reddish than that from the carbon filament at the same temperature. Consistent with this, if tungsten and carbon are compared under a condition of illumination such that their colors, as objects illuminated by some other source, may be compared — a rather difficult but not impossible condition — it will then be found that by the reflected light the color contrast is just the reverse.

Following out this viewpoint, one would expect certain effects in color lighting to be made possible through the selection of radiating bodies which possess strong color characteristics as objects illuminated by other sources. Unfortunately, the temperatures to which such bodies are ordinarily limited prevent the strict utilization of this idea to any extent. However, when the color discrimination is extended to include the ultra-violet and particularly the infra-red portions of the spectrum in what might be here called a "super-color" discrimination, great possibilities are found.

Opaque and Non-opaque Radiating Bodies. — Non-black bodies may also be classified on the basis of opaqueness. All bodies, if sufficiently large, are opaque to all radiations. Also, all materials, if shaped sufficiently thin, are only partially opaque, and, in general, are opaque in varying degrees for different wave-lengths. This latter characteristic of partially opaque bodies, like the color of material in opaque bodies, offers a basis for interesting and important development in light sources. Not much headway has been made on this basis from the strict color discrimination standpoint. However, it partially accounts for the high efficiency of the Welsbach mantle. Improvement seems possible in proceeding definitely on this basis in development work.

Black-body Radiation

Experimental Realization. — Black-body radiation is realized whenever there is an opaque enclosure whose temperature is uniform throughout. In practice black-body radiation is obtained from such an enclosure by means of a small hole through its wall.

The radiation from such an enclosure depends *only* on its temperature and not upon the kind of material composing it. An enclosure of carbon at 1000° K. radiates exactly the same as an enclosure of tungsten or of gold at 1000° K. This feature is extremely important for high-temperature measurements employing radiation methods.

This independence of the material means that an enclosure may consist of various materials, provided the conditions of opaqueness and uniformity of temperature are complied with, and further, that, in case the temperature is such that the cavity is self-luminous, one will not be able to distinguish the materials visually by means of their radiations. The same is true of objects within the cavity. This is quite in contrast with their appearance outside such a cavity. In practice, the disappearance of detail in an enclosure heated to incandescence is a working criterion to indicate the attainment of a uniform temperature.

FIG. 7. Diagram Illustrating How a Beam of Radiation Entering a Small Hole in a Circular Enclosure is Finally Almost Completely Absorbed in the Enclosure (Black Body) and conversely, Regardless of the Material of the Enclosure, How its Radiation Builds Up into Black Body Radiation.

The Attainment of Complete Absorption. — In Fig. 7, a beam of radiation is represented diagrammatically as entering a small hole in an enclosure with a spherical, polished, interior surface. The change in width of the lines drawn to represent the path is meant to show the successive changes in the intensity of the beam as it is reflected back and forth. Complete absorption of any beam entering the enclosure is evident. Depending on the material of the enclosure, carbon, iron or copper, the number of reflections required for its practical accomplishment ranges from 2 or 3 to perhaps 15 or 20, but the ultimate effect is the same.

Enclosures with diffusely reflecting surfaces operate similarly and equally effectively in absorbing radiation.

The Attainment of an Emissivity Power of Unity. — Conversely, in the emission process there is a building up of radiation so that what is emitted from a small opening in the walls of a uniform-temperature,

opaque enclosure is black-body radiation. Thus, to that radiation which naturally has its source at the surface directly back of the opening in the line of sight, there is added by reflection radiation which originates elsewhere. Some of it undergoes but one reflection, some two, some three, etc. It is built up in much the same manner that entering radiation is absorbed. The number of reflected beams required to produce radiation which is practically black differs with the material, but the final effect is the same so far as the radiation from the opening is concerned.

Black-body Laws. — Black-body radiation follows certain known theoretical laws. Because of this, the temperature of a black-body source is always measurable. Temperatures of other sources, particularly when the temperatures are very high, have thus far been measured only in terms of, or by means of, black-body radiation which may be in some way connected with the temperatures to be measured.

The laws which have been referred to are Stefan-Boltzmann's law,

$$E = \sigma T^4,$$

Planck's law,

$$E_\lambda = \frac{C_1}{\lambda^5}\frac{1}{\epsilon^{\left(\frac{C_2}{\lambda T}-1\right)}},$$

Wien's distribution law, a valuable approximation of Planck's law for visible radiation,

$$E_{\bar{\lambda}} = \frac{C_1}{\lambda^5}\epsilon^{-\frac{C_2}{\lambda T}},$$

and Wien's displacement law,

$$\lambda_m T = \frac{C_2}{4.9651},$$

in which E represents the total rate of emission of energy per unit of area and is measured in watts per square centimeter, T the absolute temperature in °K., λ the wave-length in μ, E_λ any ordinate of the spectral energy curve in watts per square centimeter per centimeter interval of wave-length. λ_m the wave-length for which the ordinate of the spectral energy curve is a maximum, ϵ the base of the Naperian logarithms and σ, C_1 and C_2 constants whose respective values in the ordinary system of units are approximately 5.70×10^{-12} watts per sq. cm. deg.^{4}, 3.72×10^{-12} watts per sq. cm. and 1.433 cm. degrees.

The Stefan-Boltzmann law states, for instance, that a black body at 2000° K. radiates energy at a rate which is 2^4 or 16 times as great as it

does when at 1000° K. This law is theoretically sound and does not depend for its derivation upon any assumed properties of matter. Though the best grounded of the black-body laws, it is relatively little used in actual measurements of temperature.

Planck's law gives the spectral energy curves of black-body radiations. It shows (Fig. 8) how the energy radiated is distributed as to wave-length.

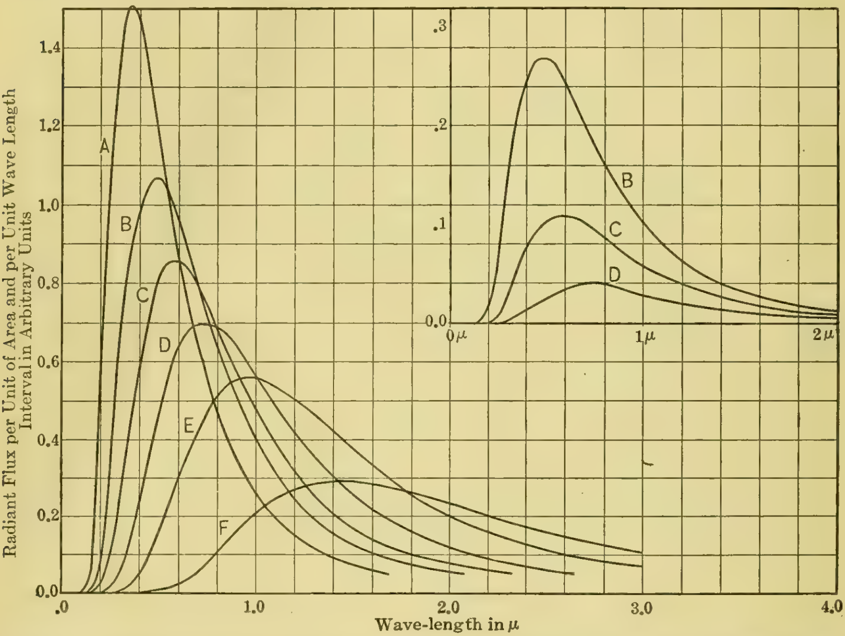


FIG. 8. Spectral Radiant-Flux Curves for a Black Body at Various Temperatures.

A 8000° K	D 4000° K
B 6000° K	E 3000° K
C 5000° K	F 2000° K

Note: At the right, curves, B, C and D are shown drawn to the same scale. To obtain the proper relative values of the ordinates, the values obtained from the curves B, C, D, E and F at the left must be divided by 3, 6, 15, 50 and 200 respectively.

Wien's displacement law shows a characteristic change in spectral distribution with change in temperature. It is well illustrated in Fig. 8. Special attention should be directed to the note accompanying the figure. When the curves are drawn to the same scale, as in the upper right-hand corner, there are no intersections of one curve with another. One can readily see that an increase in temperature is accompanied by a shift of the radiation, generally from the infra-red toward the visible

and ultra-violet portions of the spectrum. This shift is naturally accompanied by a like shift in λ_m. The quantitative statement giving this shift is the law being discussed.

Shift in the Spectral Energy Curve with Change in Temperature. — The shift of the spectral energy and spectral luminosity curves toward shorter wave-lengths with increase in temperature is characteristic of all radiations due to temperature. Thus, an ordinary incandescent lamp, as it is gradually heated up to normal brilliancy, passes through the stages of a dull red, bright red, orange and orange-white, while the spectral energy curve maximum shifts gradually from the far infra-red to the near. For evident reasons, this shift in the spectral energy curve is a very important factor in determining the best conditions of operation for incandescent light sources.

Luminous Efficiency. — Given the visibility curve and the laws of black-body radiation, it is only a matter of labor to obtain the spectral luminosity curves of a black body for various temperatures. Determinations of the luminous efficiency of black-body radiation, using the luminous and the radiant fluxes thus determined, show that it first increases with the temperature, passing through a maximum value of about 90 lumens per watt at 6500° K., and thereafter decreases slowly.

The cause for this change is shown in Fig. 8. As the temperature increases, starting from some low temperature, the center of the radiation spectrum shifts gradually from far in the infra-red toward the visible, into and through the visible, toward and into the ultra-violet. Any process or shift which tends to throw greater and greater portions of the energy radiated into the visible spectrum will obviously increase the efficiency of the radiation, and any process or shift which tends to throw greater and greater portions into the ultra-violet spectrum will likewise decrease the luminous efficiency. Both processes operate at all temperatures; however, below 6500° K., the former is the more effective, hence the gradual increase in efficiency; at 6500° K. the two shifts are equally effective, hence the passing through a maximum. At this temperature the effective center of the spectral energy curve occurs at nearly the wave-length of maximum visibility.

Crova Wave-length. — For each change in temperature of a source there is a certain wave-length, the Crova wave-length, for which the corresponding luminosity varies at the same rate as does the total luminous flux. Thus the brightness of a black body at 5000° K. is 30.2 times that at 3000° K. As may be verified from Fig. 8, this is also the change in spectral brightness at 0.562μ. For wave-lengths longer than 0.562μ the change is not so great; for shorter wave-lenghts

the change is greater. For the particular temperature change the average change coincides with the actual change at 0.562μ, which is, therefore, the Crova wave-length. The exact value for any source changes somewhat with temperature. However, for many purposes, it may be considered constant. This assumption is often made in computations where approximate values are satisfactory. Using such a Crova wave-length and Wien's approximation for Planck's law, it is easy to compute the changes in the luminous flux from a black body with change in temperature. The corresponding change in radiant flux may be computed directly by means of Stefan-Boltzmann's law. From the two there may be obtained by simple division the change in luminous efficiency of black-body radiation with change in temperature.

Importance of Black-body Sources. — The importance of black-body radiators as sources of light is not dependent on their inherent luminous efficiencies as measured in lumens per watt, for non-black radiators at the same temperatures are usually more efficient. Black-body radiators are important as sources, however, in cases where, without regard for efficiency, high brightnesses are desired, since for a given temperature the black-body source (excluding cases of luminescence) has the higher brightness. But most of all, black-body sources are of importance because they serve as standards following known laws, and, therefore, may be, and are, much used in the study of other sources.

The Sun

[A. G. Worthing]

General Characteristics. — Man's most important illuminant is the sun. With a diameter of 1,390,000 km. (865,000 miles) and a temperature far in excess of any sustained temperature obtained in the laboratory, the sun is nevertheless only moderate in dimensions, temperature and brightness when compared with other stars of the universe. From the standpoint of mankind, however, it is unique. Its distance from the earth, about 150,000,000 km. (93,000,000 miles), is only 1/270,000 of that of its nearest neighbor. On account of their remoteness, these other stars, though probably to be reckoned by billions, contribute inappreciably, in comparison with the sun, in supplying the earth with light and heat.

In describing the sun, Abbot states in his book, " The Sun ": " As viewed through the telescope, or photographed, the radiating surface of the sun called the photosphere (light sphere), presents a brilliant disk covered by indistinct mottlings sometimes spoken of as the ' rice-grain-structure.' Objects much less than a second of arc or 400 miles in

diameter cannot be well seen on the sun, so that these rice-grains which appear . . . from 100 to 500 miles in diameter are really large areas. . . . Generally a few dark patches (only relatively so, since compared with terrestrial sources they are still intensely bright) called sun spots may be seen, and around them if they happen to be observed near the edge or limb of the sun are found very bright areas called faculæ. . . . Photography reveals at once, what the eye recognizes less easily, that the photosphere falls off in brightness towards the sun's limb."

At about 5 per cent of the sun's radius from the edge, the brightness is little more than half of that at the center. The falling off differs with the wave-length, the shorter wave-lengths decreasing more rapidly than the longer ones. As a consequence, the edge of the sun appears reddish when compared with the central part.

Surrounding the photosphere is the chromosphere (color sphere). It consists of luminescent vapors. Measurements indicate that the chromosphere is about 10,000 km. (approximately 6,000 miles) in thickness. Whether or not it is separate from the underlying photosphere, as is our atmosphere from the solid earth, or whether the one merges gradually but rapidly into the other is not known.

Outside the chromosphere, at times of total solar eclipse, a pearly-hued haze, the corona, may be seen, which streams irregularly in all directions from the sun as a center and extends outward for varying distances of the order of one or two solar diameters. The light from the corona is due in part to its own high temperature, and in part to reflection of light from the photosphere. The exact nature of the corona is still doubtful. However, since the sources of the streamers at any time seem to coincide with centers of eruptions on the sun's disk, its origin, as well as its shape, is probably due in large measure to explosive ejections of matter from the more dense portions. The tremendous violence of these eruptions produces prominences which are sometimes traceable outward for distances equal to a tenth and sometimes even a third of the sun's diameter.

A further idea of the magnitude of these phenomena may be gained from the fact that many sun spots are sufficiently large to take in at one time several bodies of the size of the earth.

Brightness. — The intensity of the sun's radiation over its disk varies greatly. The maximum values of illuminations at the earth due to the sun, taken in connection with its size and distance, lead to a value of about 200,000 $\frac{\text{candles}}{\text{cm.}^2}$ for its brightness. This is about 15 times that of the crater of the open carbon arc. (See Table II.)

TABLE II

TEMPERATURE, T; COLOR TEMPERATURE,* T_c; BRIGHTNESS, B; AND LUMINOUS EFFICIENCY, E; FOR VARIOUS LIGHT SOURCES

Source	T in °K.	T_c in °K.	B in $\frac{\text{candles}}{\text{sq. cm.}}$	E in $\frac{\text{lumens}}{\text{watt}}$
Sun — outside of earth's atmosphere				
measured	....	6500	200,000	100
computed	....	6500	224,000	113
at horizon	....	....	600	....
Clear sky (average)	....	....	0.4	....
Black body at 6500° K	6500	6500	294,000	90
4000° K	4000	4000	24,350	52.2
Arcs				
Searchlight arc	....	....	50,000 to 70,000	....
Crater of solid carbon arc	....	3700	16,000	....
Tungsten arc	3655	3800	5,560	....
Flaming arc (white)	....	....	....	23
Hg-vapor arc (glass)	....	....	2.3	14
Moore CO_2 tube	....	....	0.1	....
Incandescent lamps				
900-watt tungsten moving-picture (as operated)	3350†	....	2,700	....
(in open space)	3290	3220	2,630	27.3
1000-watt gas-filled tungsten	2990	2980	1210	20.0
500-watt gas-filled tungsten	2930	2920	1000	18.1
100-watt gas-filled tungsten	2760	2740	579	12.9
40-watt vacuum tungsten	2465	2515	203	10.0
2.3-w. p. c. Nernst	....	2400	258	...
2.0-w. p. c. Tantalum	....	2260	53.1	5.0
2.0-w. p. c. Osmium	....	2185	60.8	5.0
2.5-w. p. c. Gem	....	2195	78.1	4.2
3.1-w. p. c. Treated carbon	....	2165	70.6	3.4
4 -w. p. c. Untreated carbon	....	2080	54.9	2.6
Flames				
Acetylene (as a whole)	....	2380	....	....
(one spot)	....	2465	6.7	....
Mees burner	....	2360	10.8	....
Gas flame — Bat's-wing	....	2160	0.4	....
Candle shape 10 cm. high	....	1875	....	....
Kerosene — Flat wick	....	2055	1.27	....
Round wick	....	1920	1.51	....
Candle — Sperm and paraffin	....	1925–30	0.5	...
Hefner	....	1880	....	.. .
Pentane — 10 cp. standard	....	1920	....	....

* See page 96.
† Approximate.

Temperature. — Estimations of the sun's temperature have been based upon the intensity and the spectral character of its radiation. The estimates usually assume the radiations to be due to temperature alone and in fact to agree either in intensity or distribution with that form a black body at the same temperature.

The use of the Stefan-Boltzmann fourth-power law is simple. Measurements by the Smithsonian Institution have yielded 1.932 $\frac{\text{calories}}{\text{cm.}^2\ \text{min.}}$ for the solar constant, the rate of the impinging of the sun's total radiation on a surface normal to it at the earth's orbit. This combined with the fourth-power law, with $5.70 \times 10^{-12}\ \frac{\text{watts}}{\text{cm.}^2\ \text{dg.}^4}$ as the empirical constant, has led to 5900° K. This value represents a lower limit.

How Wien's displacement law, which deals with the shift with temperature of the wave-length, λ_m, at which the radiation intensity is a maximum, and Planck's law, which deals with the spectral energy curves, are applied is shown in Fig. 9. These two methods yield approximately 6200° K. and 7200° K., respectively.

Efficiency of Solar Radiation. — Given the solar maximum illumination outside the earth's atmosphere and the solar constant, simple computation shows the luminous efficiency of the sun's radiation to be about 100 $\frac{\text{lumens}}{\text{watt}}$. This is slightly greater than the maximum efficiency

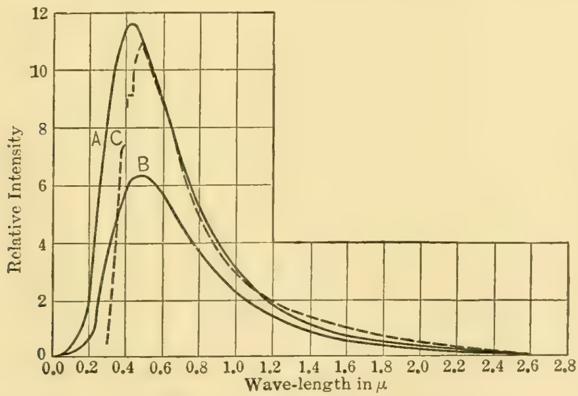


FIG. 9. Spectral Energy Curves for
A. A Black Body at 7000° K. (computed)
B. A Black Body at 6200° K. (computed)
C. The Sun. (observed)

of black-body radiation, 90 $\frac{\text{lumens}}{\text{watt}}$. The explanation of this difference is indicated in Fig. 9. The spectral energy curve of the sun differs from that for a black body at 7000° K. (approximately that corresponding to the maximum luminous efficiency of black-body radiation) but little in the infra-red and in the visible region. However, at the blue end of

the visible spectrum where the visibility of radiation is low and in the ultra-violet where it is zero, the sun's spectrum is greatly reduced. The effect is an approximate brightness quality, though the radiation intensities are quite different and are such as to give the increased efficiency to the sun's radiation.

It is an interesting fact and possibly significant in the evolutionary development of the human race that the wave-length of maximum visibility, 0.556μ, does so nearly coincide with the wave-length of the maximum in the sun's spectral energy curve plotted on a wave-length basis, consideration being taken of the enveloping atmosphere.

Spectrum. — The central part of the sun always shows dark lines across an otherwise continuous spectrum. As the edge is approached the contrast between these dark lines and the continuous background decreases. At the edge itself is the bright-lined spectrum of the chromosphere. The dark lines in the spectrum of the center are only relatively dark; at those wave-lengths radiation is present, but not to so great a degree as at the neighboring wave-lengths.

By comparing the dark lines of the sun's spectrum with bright-lined spectra obtained in the laboratory, one may form some conclusions as to what elements exist in the sun's chromosphere. These spectra, for instance, show unmistakable evidence of the existence of iron in the sun's chromosphere or "reversing layer," as it is often called when its activity in producing the dark lines is being considered. Many common elements have been detected in the sun, among them H, Ca, Fe, Ba, Na, Mg, Mn, T, Sr and Cr. These elements in vapor form, at extremely high temperatures in the chromosphere, partially or completely ionized, absorb from the radiation from the photosphere those wave-lengths which the elements themselves are capable of radiating and reradiate them, with various frequencies, not in the direction in which they were proceeding before their absorption, but in all directions; hence the apparent lack in certain wave-lengths. The gradual change in intensity as the edge of the sun is approached and the bright-lined spectrum of the chromosphere at the edge are due, as already suggested, to the gradually increasing effective thickness of the outer absorbing and scattering layer.

Type of Radiation Emitted. — A direct connection has been noted between certain solar and terrestrial phenomena, viz., aurora and magnetic storms. These as well as certain spectral evidence point to the surface of the sun as the seat of tremendous electromagnetic disturbances. Probably, therefore, an appreciable part of the radiation is due to luminescence. If so, the explanation of the continuous character of the spectral energy curve is in part to be ascribed to the high

pressures experienced in the photosphere. It is evident also that a great portion of the radiation has a strictly thermal origin.

Source of Energy Radiated. — One of the great mysteries, until recent years, has been the means whereby the sun has been able to maintain its high temperature but little changed during past geologic ages despite the present staggering radiation loss of 3.8×10^{26} watts (a rate representing the melting of 300,000,000 cubic miles of ice per second) which must have been kept up throughout. Geologists have demanded a sun that should maintain the earth's temperature roughly constant for 50,000,000 or 100,000,000 years. Until recently, physicists, assuming that the energy was due to the change of potential energy into kinetic energy which accompanied the gradual shrinking of the radiating mass, have admitted of a considerably lessened interval for the period of approximate constant incandescence. However, the discovery of radioactivity and of the relatively immense amounts of energy that may be released by intra-atomic changes seems to render plausible the continuous supply demanded by geologists.

Note. — In the following sections on gas, electric incandescent and vapor tube lamps, A. G. Worthing has contributed portions on the physics of light production.

Illuminating Gas and Other Flame Sources

[H. Lyon]

According to the nature of their radiations, flame sources are classed as luminescent or incandescent. The luminescent class contains many individual types; but, possibly because the effects which can be obtained by them may usually be obtained more satisfactorily otherwise, for instance by the flaming arc, very little use is made of them for illumination purposes. For the use that has been made, reliance has usually been placed on their great color possibilities. In this connection, flames burning salts of sodium, potassium, calcium and other alkali and alkaline earth metals are most valuable. Their spectra are always of the bright-lined type. While luminescence in flames is usually ascribed to chemical action, in a more specific way it is ascribed to the recombination of electrons and ionized atoms and to the return to equilibrium of atoms following electrical impacts between them and other electrons, ionized atoms and neutral atoms. It is well known that flames are rich in ions.

Sources of the former class include most, if not all, that were used for illumination purposes up to the advent of the commercial electric arc, among them the oil lamps of the ancients, the candle and kerosene lamp, as well as the more recent ones using coal gas, Pintsch gas, carburetted air gas and acetylene.

A little over one hundred years ago, Murdock in England first produced gas by destructive distillation and made a test of lighting by gaseous fuel conducted through pipes. At first, the combustion process was not understood, as it was thought to be something that involved the gas alone rather than its union with air, and so grave fears were entertained as to the possibility of storing the gas in holders to be delivered variously through piping to burner outlets.

Illuminating gas produced by destructive distillation is a complex of many different gaseous compounds, together with the elementary gas, hydrogen (H), and some inert nitrogen (N). It is produced by the destructive distillation of almost any organic compound, notably coal, with a good measure of volatile ingredients.

Constituents. — Bodies of the

1. Paraffin series, as Methane, Ethane, Propane, Butane, etc.
2. Olefin series (unsaturated) as Ethylene, Propylene, Butylene, etc.
3. Acetylene series, as Acetylene, Allylene, Crotonylene, etc.
4. Benzene series, as Benzene, Toluene, etc.

Carbon monoxide and sulphur are also constituents of coal gas. The larger percentage of the constituents of coal gas are normally gaseous bodies, but some, as pentane, butylene, benzene and toluene, readily condense to liquid form at low temperature or moderate pressure.

TABLE III

Sample Analysis of Gas (Per Cent Volume)

	Coal	Water (Carburetted)
H (hydrogen)	47.04	32.4
CO (carbon monoxide)	8.04	30.7
CH_4 (methane)	36.02	13.9
C_6H_6 (benzene)	.5	.6
Heavy hydrocarbons, ethylene, etc.	4.25	12.8
Higher paraffins	0.00	2.4
CO_2 (carbon dioxide)	1.6	2.7
O (oxygen)	.39	.70
N (nitrogen)	2.16	3.8

Coal gas is manufactured from coals having a rather large percentage of volatile ingredients as, for example, 17 to 35 per cent. According to the volatile portion, a ton of coal will yield from 9000 to 13,000 cu. ft. of gas. In general, coals that are classed as bituminous are suited for the manufacture of coal gas.

Manufacture. — In the manufacture of coal gas, coal is placed in a retort capable of being hermetically closed and subjected to external

heat to drive out volatile ingredients in the form of gas, tar, water vapor, etc. The residue is coke. In fact, illuminating gas is a by-product of coking when the primary object is the manufacture of coke for use in smelting furnaces.

Whether coal gas is to be used for heating or lighting, it must be purified in order to be freed from tar, sulphur, etc. As the process of purification is similar to that used for water gas, a description of methods of purification will be given in connection with the discussion of water gas.

Water-gas Manufacture. — A rating of illuminating gas that designates its heating power is expressed in British thermal units, which expression is commonly abbreviated to B.t.u. A British thermal unit designates a perfectly definite quantity of heat, namely, the quantity of heat required to raise the temperature of 1 lb. of water 1° F. A 570 B.t.u. gas is one that by burning 1 cu. ft. will raise the temperature of 570 lbs. of water 1° F. A 20-candlepower gas is one which by burning at the rate of 5 cu. ft. per hour in an open-flame burner will give 20 candles in a horizontal direction.

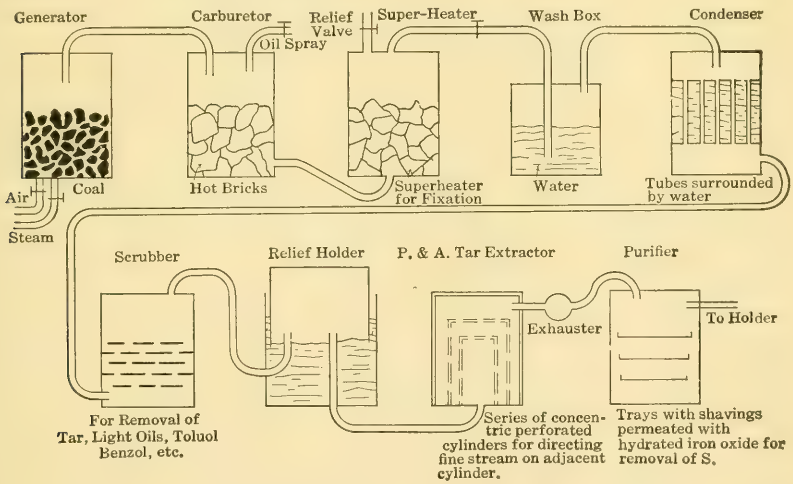


FIG. 10. Illustrative Diagram of Water Gas Apparatus.

Water gas is manufactured from anthracite coal, 30 lbs. of coal yielding about 1000 cu. ft. of gas. The coal is introduced into a generator, Fig. 10, and is kindled as a coal fire. Air is forced into the generator until the entire mass of coal is glowing. Then the air is shut off and steam is forced through the mass of hot coals. This is known as the "run." In the lower part of the generator, water is decomposed into hydrogen (H) and oxygen (O), and an atom of carbon (C) takes up two atoms of

O, forming carbon dioxide (CO_2). In the upper part of the generator, $CO_2 + C$ forms two molecules of carbon monoxide (CO). CO and H pass on into what is termed the carbureter.

Such a mixture would burn with a blue, non-luminous flame and be of rather low heating value, about 300 or 350 B.t.u. It would not be at all suited to give light in an open-flame burner. To give it a higher B.t.u. value and render it capable of producing luminosity, about 4 gallons of oil per 1000 cu. ft. of gas are sprayed into the carbureter and the vapor passes along with the gas over a mass of heated bricks. Carburetted water gas has a B.t.u. value of about 650 and burns with a luminous flame.

In the carbureter, the oil is broken up into various hydrocarbons by a process known as "cracking." From the carbureter, the gases pass on into a second chamber known as a "superheater." This latter also contains hot bricks but is of somewhat lower temperature than the carbureter. The object of this process is to fix the form of the various gaseous and semigaseous bodies. If too great heat were applied in the superheater, hydrocarbons would be broken up into C (solid) and H, and the heat and illumination values would be lessened.

The coal in the generator is quickly cooled by the steam. A run lasts but a few minutes and must be followed by a "blow." That is, the original process of forcing in air to bring the coal again to a glow must be repeated and this in turn must be followed by a second run, and so on until the mass of coal is used up. The bricks in the carbureter and superheater are kept hot by forcing air in at intervals. The oxygen of the air in combination with gas again raises the temperature of the bricks to a glowing condition.

Purification. — From the superheater, the gas passes through a tube into a wash box, the tube terminating under water. Thus the gas is cooled and in a measure freed from tar. Thence the gas passes into a "condenser" for further cooling and further tar removal. The condenser is fitted with tubular passageways arranged to be surrounded with water. The gas then enters a scrubber, which is a chamber fitted with trays or slats that expose large surfaces to passing gas. In the scrubber still more tar is removed along with light oils. Thence the gas passes into a relief holder (merely a gasometer) and following this to a specially designed (P. and A.) tar extractor. Now the gas is forced along by an exhauster into a purifier filled with trays carrying shavings impregnated with hydrated iron oxide, for the removal of S, which is accomplished through a sort of catalytic action on H_2S. From the purifier the gas passes into the well-known holder for storage and

transmission. When oils are high in price, it is a common practice to supply to consumers coal gas or coal gas and water gas mixed.

There is a marked general movement at this time to remove the legislative requirement for a specific candlepower gas and substitute a B.t.u. standard. Such gas would not be suited to an open-flame burner, as it is deficient in hydrocarbons.

Other gases employed in illumination are:

1. Acetylene produced by the action of water on calcium carbide (CaC_2, formed in the electric furnace by the reaction of coke and CaO). The reaction is as follows: $CaC_2 + H_2O = CaO + C_2H_2$.

2. Blau gas, manufactured from oil.

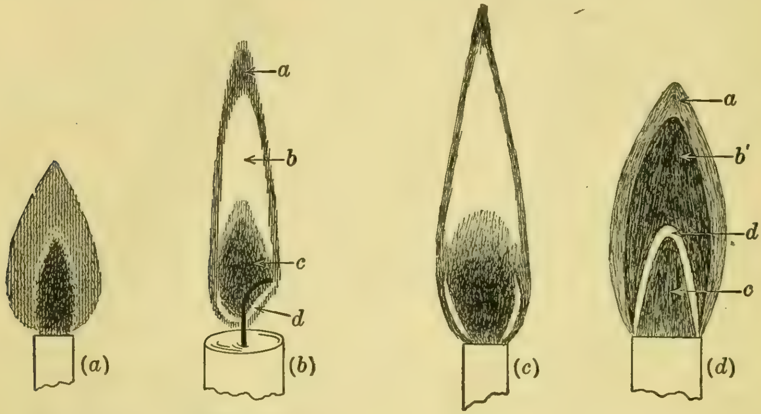
3. Producer gas, made by passing a limited amount of air over hot coal and necessarily containing N as a part of its composition. Acetylene is excellently adapted to isolated plants. Vaporized gasoline is also supplied to burners in isolated plants and burns as a gas to produce mantle incandescence.

Only gases known as hydrocarbons yield free C on burning and *only* such gases give appreciable light. In each case, light production is a consequence of the breaking down of the hydrocarbon fuel while in a gaseous state and the formation of carbon particles which, previous to their ultimate oxidation, radiate because of their high temperature. To put it in another way, the illuminating power of gases when used in the open flame is due to the incandescence of particles of C freed from their combination and floating through the flame where they are finally consumed at the border on reaching a supply of secondary air. In conformity with this, hydrocarbon flames give continuous spectra and match in color almost perfectly with black bodies at suitably chosen temperatures.

Structure of a Hydrocarbon Flame. — A visual inspection of the flame of an ordinary candle shows a structure (Fig. 11 *b*) characteristic of most, if not all flames of hydrocarbons burning in air. Four distinct regions are to be seen, viz.: (*a*) a faint, thin, blue enclosing sheath; (*b*) a large, bright, yellow-white dome; (*c*) a large, dark space; and (*d*) a bright, blue, thin layer between the outer sheath and the dark space. Exact counterparts of these are found in the luminous Bunsen flame (Fig. 11 *c*). In the non-luminous Bunsen flame (Fig. 11 *d*), however, there is no counterpart of the large, yellowish-white dome. By the gradual opening of the air vent of the Bunsen burner, it is readily seen that the portion (*d*) of the luminous flame is identical with the inner cone of the non-luminous flame. Since the non-luminous Bunsen flame is a luminescent flame, this transformation shows in a significant way

the relation of the two types of flames to one another. In all incandescent flames there are associated many strictly luminescent radiations.

The products of combustion are H_2O, CO_2 and N, the N being merely an atmospheric associate of O. Exactly what processes occur in various portions of the flames is not surely known, though the general plan is



(*a*) - Structure of hydrogen flame in air
(*b*) - " " candle
(*c*) - " " luminous Bunsen flame
(*d*) - " " non-luminous Bunsen flame

FIG. 11. Flame Structure.

certain. In the dark space, fuel streams upward and outward and is gradually heated on the way to the flame boundary. On the way and to some extent after passage through the flame boundary, the more complex hydrocarbons of ordinary coal gas, for instance, break up into simpler hydrocarbons, such as methane and acetylene, and into free hydrogen and free carbon. At the lower outer edge of the dark space, the temperature is sufficient to bring about this decomposition of fuel. The oxygen of the air, which diffuses in, reacts here directly with the fuel in gaseous form and gives only a luminescent spectrum, the visible, bright blue radiations of which are associated with the forming of CO. Higher up, the carbon set free collects into small particles which, in consequence of their own oxidation of the energy set free by the oxidation of the other breakdown products about them, are raised to incandescence and radiate energy into the surrounding space. As sources of radiation, they act like ordinary solid carbon heated to incandescence. As they are carbon, their radiation is only slightly different from blackbody radiation and is subject to the same general variation with temperature. Originating in the same region, however, there are also luminescent radiations corresponding to the oxidizing of the breakdown

products which have retained a vapor form. They are comparatively very weak, however, and, moreover, are of such frequency as to be of little effect visually. In the outer sheath, oxidation to CO_2 and H_2O takes place for the remaining fuel. The color of this sheath is associated with the transformation of CO to CO_2, since the formation of H_2O is not accompanied by visible radiation.

TABLE IV

Approximate Volumes of O and N and of Air for Complete Combustion of One Volume of Gas

Flame Constituents			Air	Total Products (Volumes) per Cu. Ft. Gas			Total Products
Gas	O	N_2		CO_2	H_2O	N_2	
CO......	$\frac{1}{2}$	$\frac{4}{2}$	$2\frac{1}{2}$	1	...	2	3
C_2H_4....	3	12	15	2	2	12	16
C_2H_2....	$2\frac{1}{2}$	10	$12\frac{1}{2}$	2	1	10	13
CH_4.....	2	8	10	1	2	8	11
H_2.......	$\frac{1}{2}$	$\frac{4}{2}$	$2\frac{1}{2}$	...	1	2	3
C_6H_6....	$7\frac{1}{2}$	30	$37\frac{1}{2}$	6	3	30	39

Table IV and Fig. 12 show the approximate number of volumes of O_2 and N_2, and consequently of air, required to burn one volume of each of several gases. One cu. ft. of CO, for example, would require $\frac{1}{2}$ cu. ft. of oxygen for complete combustion and approximately 4 times as much nitrogen would be carried along with the oxygen. The volume of nitrogen would be more exactly 3.76 times the volume of oxygen required, but the factor 4 is used for simplicity of illustration. The quantity of air needed for complete combustion is more nearly 4.8 times the quantity of oxygen required.

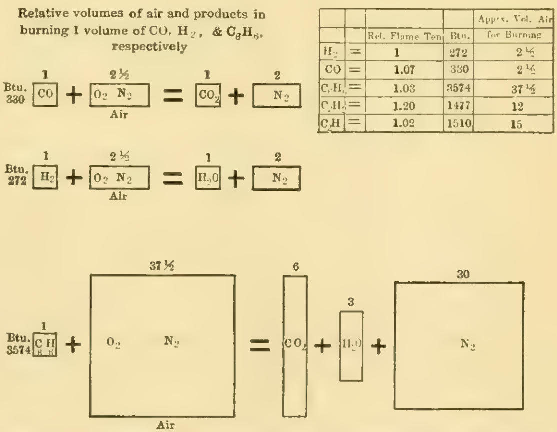


Fig. 12. Relative Volumes of O, N and Products Involved in Burning One Volume of Certain Gases. Volumes are proportional to areas.

Several conditions favor luminosity of the open flame: (1) flame temperature, (2) carbon content of the gas, and (3) manner in which the hydrocarbons are broken up.

Flame Temperature. — The actual temperature of a flame depends upon:

(*a*) The number of heat units resulting from union with oxygen of the air;

(*b*) The dampening effect due to the heat absorbed in raising the end products to a higher temperature;

(*c*) Radiation of constituents;

or in other words, on the nature of the fuel and the conditions of burning.

H_2O vapor, N and CO_2 have a marked dampening effect. N is the serious drag on flame temperature, for it is present in the air in the proportion of four volumes to one of oxygen, and is in no degree a producer of heat but must be raised to higher temperature by the other gases which in burning do produce heat. The oxy-hydrogen or oxy-acetylene flame finely illustrates possibilities in flame temperature without the incubus of N.

The determination of flame temperatures is very difficult. The results are rather discordant, though for luminous hydrocarbon flames they are much less so than for the non-luminous hydrocarbon flames and other flames generally.

A method of measurement often used involves a knowledge of the heat produced and absorbed by the products of combustion. An inspection of Table V shows the line of reasoning involved in calculating relative flame temperature when the relative amount of heat produced and the amount absorbed by the products of combustion of equal volumes are known.

The fractions representing the relative rise of temperature per B.t.u. multiplied by the related B.t.u. values for the gases will give the relative rise of temperature.

It may be understood that the values of relative rise of temperature in Table V are only illustrative and are based on the assumption that specific heats as given are uniform for a wide range of temperature, which is far from the fact. True flame temperatures are given in Table VI.

Table VI shows for a number of gases the B.t.u. values (low), flame temperatures (° K.), and the relative (approximate) rise of temperature given by simple calculation. "Low" value as applied to B.t.u. signifies the amount of heat yielded by combustion exclusive of that returned by condensation of water vapor.

TABLE V

Relative Quantities of Heat Absorbed in Heating One Volume of Products 1° F. and the Total Relative Heat Absorbed by the Products of Combustion in Burning One Volume of Specific Gases.

Products	Rel. Wt. of Equal Volumes	Specific Heat	Rel. Ht. Absorbed per Equal Vol.	Relative Heat Absorbed by Products of Combustion of the Following, per 1° F. Rise in Temperature:					
				C_2H_4	CH_4	CO	C_2H_2	H_2	C_6H_6
N_2	28	.24	6.72	80.6	53.7	13.44	67.2	13.44	201.6
H_2O	18	.475	8.55	17.1	17.1	....	8.5	8.5	25.6
C_2O	44	.201	8.8	17.6	8.8	8.8	17.6	....	52.8
Total relative heat absorbed in complete combustion by all the products (approximate) for 1 volume of gas				116.7	80.5	22.5	94.4	22.2	283.4
(A) Reciprocal of heat absorbed = relative rise of temperature per 1 B.t.u				$\frac{1}{116.7}$	$\frac{1}{80.5}$	$\frac{1}{22.5}$	$\frac{1}{94.4}$	$\frac{1}{22.2}$	$\frac{1}{283.4}$
(B) Heat produced — B.t.u. (Low)				1510	919	330	1477	272	3574
Product A × B				12.9	11.4	14.7	15.6	12.3	12.6
Relative (approximate) rise of temperature				1.12	1	1.28	1.36	1.07	1.10

TABLE VI

Certain Gases	Heat Produced per Cu. Ft. B.t.u.'s (low)	Approximate Relative Rise of Temp.	Flame Temp. ° K.
CO	330	1.28	2100° K.
C_2H_4	1510	1.12	2000
C_6H_6	3574	1.10	2016
CH_4	919	1.00	1850
H_2	272	1.07	1960
C_2H_2	1477 (P)	1.36	2130 (Lava tip burner)
Coal	480–650	......	1880 (Bat's wing burner)
Water	450–600	......	2000

In round numbers one may take as the average luminous flame temperature 1925° K. for the candle and 2000° K. for the kerosene lamp.

In contrasting hydrocarbon fuels, it is found that acetylene gives the highest temperature. This agrees with Table VII, which shows that its heat of combustion per unit volume of combustion products is the

greatest, 1.09 $\frac{\text{kilocalories}}{\text{liter of vapor}}$ as against 0.93 for coal gas and 0.82 for methane, the principal hydrocarbon constituent of coal gas. The implied relation does not necessarily hold true when there are differences in the cooling action of the radiating luminous particles in the relative amounts of CO_2 and H_2O formed, hence in the heat conduction and convection losses, and in the concentrations of the flame for a given rate of energy consumption. Some measurements indicate, for instance, that the temperature of a Bunsen flame is lowered over 150 degrees on choking off the air supply. In this decrease the effects of all three considerations just mentioned are combined. Only for the same conditions of burning is an increase in heat combustion for different fuels necessarily accompanied by an increase in flame temperature.

Carbon Content and Lamp Efficiency. — The relative carbon content of gases, assuming reduction to CH_4 and free carbon atoms, is expressed by a formula

$$\frac{C - \frac{H}{4}}{C},$$

which shows what fractional part of the carbon atoms are freed and become available for incandescent sources in the luminous flame. In the formula C and H express the relative numbers of C and H atoms in a molecule of gas under consideration.

Applying this formula, the carbon indices for a number of hydrocarbon gases, liquids and solids vary from 0 for methane (CH_4) to 0.821 for anthracene ($C_{14}H_{10}$).

If an index is less than 0.30, the flame has poor luminosity; if greater than 0.40, the flame is smoky (without special means of introducing air). A case of the latter is kerosene ($C_{10}H_{22}$) whose index is 0.45. Smoking is prevented by draft-inducing chimneys.

The lamp efficiency of a hydrocarbon fuel and the device in which it is burned, taken together as a source, depends on the relative number of carbon particles liberated on heating and on the temperature to which these particles are heated. To some extent, the former factor is opposed to the latter. In any flame source, there is always a great loss of energy through other means than temperature radiation, the principal ones being those of convection and conduction. Other things being the same, the greater the number of carbon particles, the greater will be the portion of the energy supply which will be radiated by the incandescent particles. This consideration points to a high carbon content as a desirable fuel characteristic. Other things being

TABLE VII

DATA RELATIVE TO DESIRABILITY OF VARIOUS HYDROCARBON FUELS FOR FLAME SOURCES

Series	Fuel	Formula	State	Dens. Vapor / Dens. Air	Vol. End Products (N of Air included) / Vol. Fuel Vapor	Calorific Value in[a] Kilocal. per Gr. of Fuel	Calorific Value in[a] Kilocal. per Liter of End Products	Carbon Content % by Weight	Carbon Content Index	Illuminating Value in Candle Hrs. per 5 Cu. Ft. Fuel	Illuminating Value in Candle Hrs. per l. of End Products	Lamp Efficiency in Candle Hrs. per Kilocal.
C_nH_{2n+2}	Methane	CH_4	Gas	.554	10.56	12.05	.818	.75	.00 Poor Luminosity	5.2	.0035	.0043
	Ethane	C_2H_6	Gas	1.049	18.2	11.30	.841	.80	.25	38.7	.0150	.0178
	Propane	C_3H_8	Gas	......	......	......	......	.81	.33 Non-smoking and Luminous	......	......	......
	Butane	C_4H_{10}	Gas	......	......	......	......	.82	.37	......	......	......
	Pentane	C_5H_{12}	Liq.	......	......	......	......	.83	.40	......	......	......
	Kerosene	$C_{10}H_{22}$	Liq.	4.9	79.5	10.3	.826	.85	.45 Smoky Flame	325.[b]	.0289[b]	.0350[b]
	Paraffin	$C_{24}H_{50}$	Sol.	11.7	187.	10.35	.838	.85	.48	......	.0115[c]	.0137[c]
C_nH_{2n}	Ethylene	C_2H_4	Gas	.975	15.33	11.50	.940	.86	.50	68.5	.0315	.0335
	Butylene	C_4H_8	Gas	1.94	30.66	10.85	.888	.86	.50	123.	.0284	.0320
C_nH_n	Acetylene	C_2H_2	Gas	.912	12.45	11.65	1.090	.92	.75	240.	.136	.125
C_nH_{2n-6}	Benzene	C_6H_6	Liq.	2.70	37.35	9.50	.878	.92	.75	350.[d]	.066[d]	.075[d]
C_nH_{2n-12}	Naphthalene	$C_{10}H_8$	Sol.	4.43	59.4	9.30	.900	.94	.80	930.[e]	.111[e]	.123[e]
	Hydrogen	H_2	Gas	.069	2.89	28.6	.885		.00	......	......	......
	Coal Gas (High grade)		Gas	.39 .42	6.50	10.7	.850		.19	16.0	.0175	.0203

[a] Calorific values, as here used, assume the products of combustion CO_2 and H_2O both to be gaseous.

[b] Based on determination of 1100 candle-hours/gal. of liquid; candlepower measurements were made with the broad side of flame toward the photometer head.

[c] Based on assumption that paraffin in candle form has the same illuminating value and efficiency as have the sperm candles.

[d] Based on straight-line extrapolation of data on mixtures of benzene vapor with hydrogen.

[e] Based on data obtained from a mixture of naphthalene with coal gas. These values are subject to very large uncertainties due to the very small amount of naphthalene (about 0.0085 of 1% by volume at 16° C.) which coal gas will hold. Moreover, for fuels containing a high carbon content the straight-line relation between illuminating value and percentage fuel does not hold but leads to too high illuminating values.

the same, the higher the flame temperature within certain very high limits, the greater will be that portion of the radiation which occurs within the visible limits. The temperature of a flame, as already noted, decreases with an increase in the number of carbon particles liberated per unit volume of the dissociated vapor. In that a greater number of carbon particles per given volume means a greater rate of loss of energy by radiation and consequently a reduced temperature, this consideration points to a low carbon content as a desirable fuel characteristic. The temperature and the carbon content factors are thus somewhat opposed to each other. In practice, some sort of medium carbon content is, therefore, desirable.

Illustration of the influence of carbon content and temperature is shown to some extent in Table VII, in which data for the principal constituents of coal gas are given. As already explained, the column headed calorific value in kilocalories per liter of combustion products gives an approximate indication of flame temperature. The column headed carbon content, gives, in a rough way, the relative number of carbon particles formed. However, since the values given for illuminating value and efficiency represent the most favorable conditions of burning for each fuel, the carbon content as given is not a true index for the flames for which efficiencies are given. The carbon content given represents a maximum which may be greater than the effective content due to aërating the gas. So far as a comparison of the efficiencies of the gaseous fuels, CH_4, C_2H_6, C_4H_8, C_2H_2 and C_2H_4, neglecting the slight difference between C_2H_4 and C_4H_8, is concerned, the gradual increase in efficiency might be due to either a gradual increase in carbon content or to a gradual increase in temperature. The temperature factor explains, however, the small difference in efficiency between C_2H_4 and C_4H_8 as well as the large difference between C_2H_2 and C_6H_6. For the reason given in the note to Table VII regarding naphthalene, the conclusion that one might otherwise draw regarding naphthalene is not well founded. Unfortunately, sufficient precise data of the type shown in Table VII are not at hand for showing the deleterious effect of too high carbon content. This effect, however, has been shown in a candle-

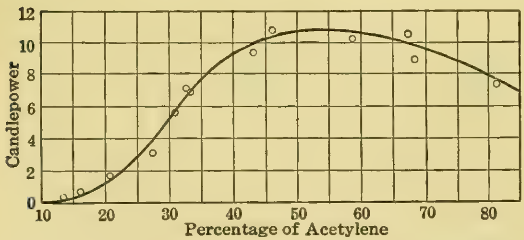


FIG. 13. The Candlepower of Flames Burning Mixtures of Acetylene and Hydrogen in Air Using a Brass-tip Burner Without Air Vents.

power test in which acetylene vapor previously mixed with hydrogen was used with a metal slit burner. Fig. 13 shows the results for varying percentages of mixtures. Starting with approximately zero candlepower for a 15 per cent acetylene flame, there was a gradual increase in candlepower with increase in the acetylene content up to about 55 per cent. With further increase in acetylene content there was a gradual decrease in candlepower. For an 85 per cent mixture, the candlepower was only two-thirds of the maximum. At these higher percentage mixtures, the flame becomes smoky, the temperature having been so lowered that not all of the fuel is consumed. For the present consideration, the point to be emphasized is that, after a 55 per cent acetylene, 45 per cent hydrogen mixture is reached, increase in carbon content due to a further increase in acetylene richness, even though accompanied by a greater calorific value per unit volume of combustion products, results in a decreased total luminosity and lamp efficiency.

Available Free Carbon at Any Given Moment. — A cubic foot of C_2H_4 and a cubic foot of C_2H_2 have the same weights of C, and consequently the same number of C atoms are concerned in the reactions at any given moment when burning at equal rates. The candlepowers of the gases (burned in open-flame burner) are as 13.7 to 48. The flame temperatures of C_2H_4 and of C_2H_2 vary as 1 to 1.17, which by the laws of black-body radiation should give for the C_2H_2 flame seven or eight times as much light as for the C_2H_4 flame. But as the candlepower of C_2H_2 is little less than four times that of C_2H_4, one must conclude that more C particles are free and incandescent in C_2H_4 or that the C particles are free and incandescent for a longer period of time. In C_2H_2, molecules may keep the form CH_4 to the border of the flame and thus not exist as free C particles for more than an inconceivably short period of time.

Fuels and Burners. — There are many types of burners. In the candle, the wick is the burner. In addition to bringing the fuel to the flame by capillary action, it serves to keep the flame away from the large body of fuel to such an extent that only sufficient energy is lost to liquefy it and thus prepare it for its transfer by capillary action.

Kerosene lamps are extensively used, particularly in country homes. The burners used in these lamps are simple and require but little discussion. The chimney and air vents control the air supply, protect from drafts, and to some extent preheat the incoming air. Kerosene has a high carbon content, and without the chimney tends to smoke. Even with the chimney it must be burned in a narrow flame in order that the oxygen of the air may rapidly penetrate the vapor and cut down to a considerable extent the formation of carbon particles by direct

oxidation of the freed carbon atoms before they have opportunity to exert much cooling effect by radiation. An optimum adjustment of wick height for maximum illuminating power occurs in each lamp. The standard illuminating power for kerosene burned in a common flat flame is about 1100 candle-hours per gallon, measured normal to the flame. The luminous efficiency of 0.035 candle-hours/kilocalorie is roughly twice that of the ordinary open coal-gas flame.

The open-flame burner using illuminating gas has practically disappeared as a light source, having yielded to the much more highly efficient and steadier Welsbach mantle and the electric incandescent lamp. The former " candlepower " specification for coal gas is giving place to one relating to heat content. The burners for open gas flames, whether constructed of metal or of lava, are essentially limited to three types. In the bat-wing burner, the gas issues from a narrow slot and forms a thin sheet of flame of much higher candlepower than one resulting from gas delivered through a round opening. In the fish-tail burner, two circular streams of gas meet at an acute angle and on ignition likewise spread out into a thin sheet of flame. In the Argand burner, parallel cylindrical jets of gas issue from a number of openings arranged in a circle and on ignition form a cylindrical flame enclosed by a glass chimney. The air for combustion is supplied from the bottom of the burner.

Acetylene light sources rose to considerable prominence in the early years of automobile lighting. The production of acetylene for town lighting was also started but its use now seems to be limited to a small number of more or less isolated dwellings and hotels, to miners' lamps and navigation buoys. The burners used with acetylene are usually lava tips with air vents. The tip is provided with jet openings that distribute the gas streams at such an angle as to make one stream abut upon the other and thus produce a flat flame. For practical purposes they are small Bunsen burners with air controls permanently fixed in such a way that the flames burn without smoke and at their maximum efficiencies. Due to its very high temperature, the efficiency of the acetylene flame is relatively high, 0.125 candle-hours/kilocalorie. It is somewhat better than that obtained with the Welsbach mantle in an ordinary coal-gas flame. Commercially, however, this advantage is more than offset by other considerations.

Pintsch gas is obtained from the destructive distillation of petroleum. It contains largely methane, CH_4, along with some heavier hydrocarbons. Compressed in tanks from 8 to 14 atmospheres, it has been largely used for railway, lighthouse and buoy purposes. Used with a Welsbach mantle, its efficiency is greatly increased.

Carburetted air gas consists usually of a mixture of air with a very volatile gasoline and is most commonly employed where the use of other artificial gas, natural gas, or electric lights is not possible or convenient.

When burned in open-flame burners, coal and carburetted water gas of 450 to 650 B.t.u. value give varying candlepowers ranging from 2.4 to 4 per cu. ft. of gas consumed. This light-giving power may be increased six or more times by burning the gas in a Bunsen burner (blue-flame, non-luminous) and introducing solid substances, other than C, that give radiation selectively in the visible spectrum.

Among solid substances having favorable radiating characteristics are the oxides of the rare earths, as erbia, yttria, lanthana, ceria and thoria. These substances, furthermore, may be formed in light masses with considerable tensile strength and their composition is stable at the high temperature of the Bunsen flame.

The Incandescent Gas Mantle. — About forty years ago, Dr. Karl Auer von Welsbach (Vienna) discovered quite accidentally that oxides of the rare earths possess the characteristics named. In examining the spectrum of erbium, he conceived the idea of saturating a cotton thread with a soluble salt of erbium and then burning out the organic material, thus leaving an oxide for spectral study. He was surprised to find on introducing the thread into the Bunsen flame that when the organic matter had burned out, a coherent replica of the original thread remained and glowed brilliantly in the Bunsen flame. This was the inception of the modern incandescent gas mantle.

This discovery was followed by efforts to produce a cylindrical or conical form by saturating loose fabric of appropriate shape for suspending over the Bunsen flame, and then burning out the organic matter. First results were not promising in the amount of light produced. Erbia as a radiating material gave only about twice as much light as could be produced by burning the same amount of gas in the open flame.

After Dr. Auer discovered the light emissivity of the erbia filament and its coherency, he investigated other bodies of the rare earth group and finally formed mantles containing ceria, lanthana and zirconia. The first commercial mantles were of such composition. These gave only $2\frac{1}{2}$ to 3 times the light obtained by burning gas in an open flame. Considering the high price of these first mantles, the results hardly justified the expenditure. Furthermore, these mantles had a fatal defect: they became soft through the action of CO_2 and H_2O, much as quicklime slacks with the elements. Further investigation led to the development of ceria-thoria mantles which were altogether superior in every way, in structural qualities, permanence, and emissivity in the visible spectrum. This discovery marked the beginning of a profitable

mantle industry throughout the world. Although these results were obtained by empirical methods, the selection of materials has been shown by careful scientific investigation to be the best possible one, considering present knowledge of suitable compounds and combinations.

Mantles of today give about six times the light obtainable by burning gas in the open flame, and contain about 1 per cent CeO_2 to 99 per cent ThO_2. They radiate energy in the portion of the spectrum that includes wave-lengths well suited to illumination. An ideal mantle material, provided it possessed sufficient strength and permanence, would be one emitting luminous radiation only, and of spectral distribution best suited to the eye.

CeO_2 (ceric oxide), when heated alone to a high temperature, has high emissive power in the visible portion of the spectrum, but it also has high emissivity in the infra-red portion of the spectrum. A mantle made of pure CeO_2, because of its high emissivity, in general, cannot approach the temperature required to give high emissivity in the visible spectrum. By its high heat-radiating quality, it keeps itself relatively cool. In consequence of this quality, a mantle made of CeO_2 is a poor light-giver. ThO_2 (thorium dioxide) has an emissive power that is in a sense complementary to that of CeO_2. It is a poor heat radiator and of low emissivity in general. In consequence of this fact, when a mantle of ThO_2 is placed in the flame of a Bunsen burner, it reaches a temperature only 130° C. below the temperature of the flame, which is about 2100° absolute. However, ThO_2 would not make an efficient light radiator because it emits so little energy in the luminous form.

If a mantle composed of CeO_2 and ThO_2 in about the proportion of 1 part to 99 be heated in a Bunsen flame, the preponderance of ThO_2 will give to the structure a very high temperature. CeO_2, to be sure, is a drag on this temperature, but its mass is so small that it cannot prevent the attainment of a very high temperature in the combined mass. At the temperature of the combined oxides, CeO_2 gains high emissivity in the visible spectrum, which it could not attain without the aid of ThO_2. Any gain in the temperature at about 2000° K. results in a remarkable increase in emissive power in the visible spectrum. This increase varies as the eleventh or twelfth power of the temperature for the luminous rays, but only as the fourth power for the total radiation. Luminous radiation of a very small mass of CeO_2 at high temperature is far greater than that of a large mass at lower temperature. Accordingly, mantle material so combined has the maximum luminous efficiency that is, the maximum efficiency in the production of radiations of wave-lengths between 0.4μ and 0.7μ. In departing from the proportion of CeO_2 to ThO_2 either way, there is a loss of candlepower of the mantle.

Lessening the proportion of CeO_2 beyond a certain point results in insufficient radiating surface. Increasing the CeO_2 beyond a certain amount results in lowered temperature, because of the large radiating power of CeO_2.

A body serving the purpose of ThO_2 is termed a "base", and CeO_2 is designated a "colorant".

Mantle weight per unit of surface has such an important bearing on luminosity as to merit consideration.

Structure. — It would be desirable from the structural point of view if mantles could be made much heavier, but if this were done, there would be a marked falling off in candlepower. Heavier strands in the finished mantle may be made by giving heavier saturation to webbing. These strands will not only be heavier, but of larger diameter and surface according to saturation, and will thus have larger capacity for receiving and radiating energy in the form of light and heat. As the amount of energy in a given flame is fixed, it is evident that larger radiation would result in lower flame temperature and consequently in a marked loss of luminous efficiency. If, on the other hand, saturation were made lighter, smaller fiber surface and consequent limited radiating area would result in loss of luminous and heat radiation even though the luminous efficiency might be high. Furthermore, such a mantle would be structurally weak.

Accordingly, there is a mantle of critical efficiency in respect to weight of mantle material per square unit of surface, as well as a mantle of critical composition with 1 part CeO_2 to 99 parts ThO_2.

The significance of flame temperature in relation to the output of light from mantles may be shown by a single illustration. CH_4 and CO give flame temperatures that bear the relation of 1 to 1.14, while the B.t.u. values of these gases vary as 919 to 330. If a mantle could be supplied with an equal number of B.t.u. by use of these gases, the efficiency of the light output from CH_4 and CO would be related as 1^{11} to 1.14^{11} or as 1 to 4.2; that is, somewhat less than three times the consumption of CO compared with that of CH_4 would give more than four times as much light.

Making a Mantle Suitable for Use in the Bunsen Flame. — First, an appropriate thread is knitted into continuous lengths of tubular webbing. The thread commonly used is of a high-grade long-fiber cotton, or ramie, or of a manufactured pure cellulose thread, formerly termed, from its appearance, artificial silk, but now called glos. The first two fibers are vegetable cells and consequently tubular. Ramie fiber is obtained from China grass.

Glos thread is made of strands of very fine cellulose of indefinite

length, each strand being essentially a rod in contrast to the tubular structure of the first two named. The treatment of these various webbings differs in certain particulars, because of the nature of the materials.

The following description will apply particularly to cotton webbing. It is of the utmost importance in mantle manufacturing that all the material and processes give a final structure of pure CeO_2 and ThO_2.

The various treatments of webbing are carried on in a manner to remove every trace of oil and of mineral matter from the webbing in order to insure purity to the ash remaining after the cotton fiber is burned off. A finished mantle is seriously deficient in structural and light-giving qualities if it carries impurities such as silica or lime.

Impurities in mantle materials lead to the following results:

1. Loss in luminous efficiency, due to the introduction of unfavorable radiants;
2. Loss in candlepower, due to shrinkage which results in decreased radiating surface;
3. Loss in physical strength (mantles containing impurities become brittle);
4. Loss in continuity of surface. (SiO_2, CaO, etc., cause the mantle ash to fuse, leaving holes.)

Results obtained in purifying webbing show approximately 0.01 per cent impurity; absorbent cotton has four times this amount of impurity.

Distilled water is used in all washing and rinsing processes, and pure chemical reagents must be employed. Even the air entering rooms where some of the processes are carried on is forced into the room through a copious spray of water, to remove dust.

The various treatments of webbing in preparation for saturating with rare-earth salts have for their object the removal of oils and the various mineral ingredients contained in all organic fibers.

Alkaline and acid treatments at once occur to chemists as a natural method of procedure. It is also readily appreciated that all reagents must be eliminated after each treatment by copious rinsings with distilled water, and whizzing. The final whizzing operation is followed by steam drying, performed in such a way that the webbing is kept well ironed out.

After saturating in properly proportioned solutions of Ce and Th nitrates, webbing is cut into convenient lengths for drying. This drying process is conducted with great care to insure a final even distribution of salts. Finally, webbing is cut into short lengths appropriate for specific mantles. Various operations are involved in pre-

paring mantles for shaping processes and for final use on burners. Cords of asbestos are used for mounting on rings and for shirring upright mantles.

Forming of mantles in the blast flame is carried on by operators who have acquired great skill in this particular art. Gas and air supplied to blast flames are filtered to be free from dust. Formed and hardened mantles are dipped into a solution of collodion to protect them from harm in packing and shipping. Finally, mantles are trimmed to length, mounted, inspected and packed in individual boxes for shipment. A finished mantle is a replica of the original fabric reduced in size and evened up in shape.

Every fiber and even the very cellular structure is repeated in the distribution of the rare-earth oxides. When cotton and ramie fibers are used, the forms are cellular; when glos is used, the ultimate forms are tiny rods.

Burners. — While the original Bunsen burner was in general laboratory use when Dr. Auer made his famous discovery, significant improvements in the device have been accomplished in the past few years.

The original form is familiar to all; a base with hose attachment and passage leading to an upward-directed orifice; a cylindrical tube mounted on the base in the axial line of the gas jet, this tube having openings or air ports on the two opposite sides and a covering collar perforated to register with air-port openings and by rotation to control the admission of air. The original laboratory burner was long and clumsy and so were the earlier forms of burners for lighting. A first marked improvement was a base with a series of minute perforations covered by a similarly perforated disk actuated by a diaphragm, the rotation causing varying degrees of closure of the orifices and thus effecting a regulation of the flow of gas. This modified burner was much shorter than the earlier burner and permitted shaping to a comely device.

All the earlier lighting burners directed the gas stream upward while many recent forms direct the stream downward. The former have come to be known as upright burners, and the latter as inverted burners. Mantles as originally used were simply suspended over the flame by an appropriate support.

It is evident that a mantle suspended in a flame cannot possibly be hotter than the flame, and the upper limit of temperature for the mantle would naturally be the temperature of the flame. A mantle cannot possibly attain the temperature of the flame because of its tendency to radiate. A body, to reach the temperature of the flame, must have zero emissivity. However, in the selection of material for a "base,"

small emissivity is desirable to enable the "colorant" to be brought as nearly as possible to the temperature of the flame. It is evident that improvements in the incandescent burner must be directed toward a better selection of materials for mantles or better transmission of heat. The latter object has been attained through improvements in burner design, directed primarily toward larger entrainment of primary air. It is evident that a mantle in a flame having an admixture of air approaching the amount required for complete combustion behaves precisely as though it had a higher temperature. That is, the luminescence goes up rapidly with increased air entrainment. Large air entrainment insures a final combustion within the meshes of a mantle.

Best results in incandescence of a mantle are secured by such an adjustment of gas and air flow as to bring the outer border of the flame just to the mantle surface; that is, to fit the flame volume to the mantle. Adjustment is a matter of experience and is readily acquired. Regulation of gas flow and air flow is provided for in some way in most burners, although a burner very recently designed has remarkable performance through a wide range of pressures and quality of gas without any provision for regulation other than that offered by the friction of flow of gas through an orifice.

In this latter burner, the flame fits the mantle by reason of provision of openings in the mantle itself for an overflow of hot products of combustion.

If a burner is under-adjusted (Fig. 14), the hot outer zone of combustion does not reach the mantle surface and the luminosity is very low. If over-adjusted, a mantle has dull incandescence because a portion of

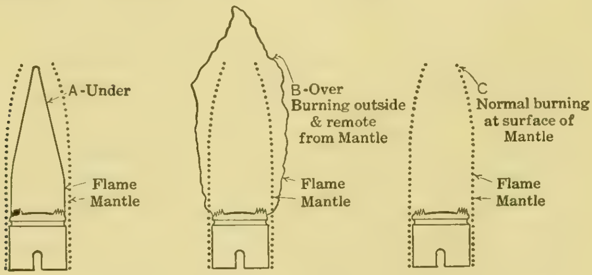


Fig. 14. Adjustment of Flame to Mantle.

the heat is delivered wholly outside and away from the mantle surface. A maximum result in temperature is secured when hot, unburned gases are consumed within the meshes of the mantle.

It would be highly desirable from the standpoint of luminous efficiency if a higher air percentage could be effected through a larger entrainment

of primary air. This is physically possible through modifications of burner structure. A Bunsen burner gives a flame consisting of an inner and an outer cone. The inner cone marks the border of the region of unburned gas. The outer cone marks the border surface at which the gas is totally consumed.

If gas were supplied with air in the quantity required for complete combustion, these separate zones would disappear and burning of a vivid character would occur at the very point of exit if the latter were very small, or flameless combustion would take place. What, then, in ordinary practice determines the boundaries of the inner and the outer cone? The translational velocity of the mixed gases at the zone border is exactly equaled by the rate at which the combining of molecules of gas and air travels back toward the burner. This rate of travel of the combining process is called the explosion rate. A flame is a form resulting from a balance of these velocities.

If more air is forced into the air port of a Bunsen burner, both inner and outer cones shorten, because the larger proportion of air to gas increases the explosion rate. If still more air is forced in, a point will be reached at which the explosion rate will exceed the translational velocity and then the burner will "flash back." This phenomenon is very familiar to the users of Bunsen burners. Flashing back may be caused variously by:

1. Increase of pressure.
2. Reduction of gas supply, resulting in excessive heating of protecting gauzes.
3. Introduction of a gas requiring less air for combustion.
4. Forcing of air into the mixture at the air ports.
5. Lessened specific gravity of a gas.

Increase of pressure causes increased entrainment because of the high velocity of the issuing gas, entraining power being definitely related to velocity. Less gas results in relatively shorter cones. A gas requiring less air for combustion mixed with a given amount of air will make a mixture that approaches an explosive mixture. By increasing air flow into the air ports, an explosive mixture must finally result. A gas of low specific gravity flows from an orifice with higher velocity and thus will entrain a larger portion of air.

In all these cases, mixtures are approaching explosive proportions, and thus, without some provision for preventing back-firing, the burner would not be a practical device. It may be said at this point that gases in general use vary considerably in composition, pressure and

specific gravity, and thus a device must be provided that has considerable adaptation to changing conditions.

A device in almost universal use consists of at least one wire-gauze diaphragm mounted in the burner outlet. By cooling the mixture below the ignition temperature, the gauze prevents the explosion wave from progressing beyond the burner head into the tube. The gauze serves a further purpose in producing an even distribution and pressure of the air-gas mixture, a condition insuring noiseless burning.

During the period that burners were operated in a manner to direct the gas-air streams upward, little difficulty was experienced in the matter of back-firing while these were in use on commercial gases. Such burners were not very efficient entrainers and so the mixtures had a rather low explosion rate. By the use of a chimney, however, a somewhat better entrainment was effected, but the most important result was due to a swift secondary current of air which coursed up through perforations in the gallery supporting the chimney and rushed swiftly past the mantle surface, insuring the burning of gases of low aëration right at the mantle surface. In this way, high incandescence was secured by the use of upright burners.

From many considerations, it seemed desirable to distribute gas downward into a sacque mantle, mounted on a clay ring. The ring carried lugs adapted to support the mantle in the path of the gas-air stream. Counter buoyancy of the hot mixture now made the problem of the efficiency of the entrainer a vital one. In some measure this entraining efficiency was attained by substituting for the original rather large cylindrical Bunsen tube a relatively short length of cylindrical tubing of smaller diameter. Such a structure, known as a "raceway," remained in general use for many years without substantial change. Earlier forms of burners of the inverted type entrained about 1/22 volume of air to one of gas. Almost all earlier forms of inverted burners required for efficient operation a cylinder of glass with openings at the bottom for admission of secondary air, which, as in the case of the upright lamp, enabled the mantle to gain high incandescence. A low order of entrainment always makes some draft-inducer necessary for satisfactory results. If primary air is not present in a certain proportion, a secondary current of air must be supplied. Incidentally a cylinder below the mantle serves the purpose of protection from fire danger by fractured rings or burner tips.

Burner outlet tubes or nozzles are made of clay and threaded appropriately for attachment to the metal portion of the Bunsen mixing tube. All mantles used on upright and inverted lamps at commercial gas pressures, until very recently, had an outlet other than that afforded by

the meshes of the mantle itself for escaping gaseous products. For upright mantles, an opening is provided at the top of the mantle by limiting the completion of the closure by the shirring cord at the top. Inverted mantles are tied on a clay ring whose inner circumference considerably exceeds that of the outer circumference of the burner tip or nozzle. The outlet of the burner nozzle is always made to extend down some distance into the mantle.

Means for preventing back-firing are far more necessary for the inverted lamp than for the upright lamp, because of the necessarily high temperature of the mixture. This is accomplished by a burner tip considerably widened at the top and provided with a gauze. The latter offers less resistance to the flow of gas and is quite effective in preventing back-fire.

In improving burners attention has been directed to the following features:

(*a*) A smooth and straight orifice with centralized needle for even distribution and regulation of flow.

(*b*) Properly proportioned air ports.

(*c*) Taper tube approach to the constriction in the Bunsen burner.

(*d*) Diameter and length of the constricted portion of the tube and the distance between the orifice and the beginning of the constriction.

(*e*) Continuation of the tube beyond the constricted portion in the form of a gradually widening tube whose object is to eliminate eddy currents and thus resistance to flow.

(*f*) Distributing passages beyond the Bunsen tube proper to insure even distribution of pressure.

The constricted throat of the Bunsen tube should have a cross-sectional area equal to 43 per cent of the outlet port or ports. Beyond the constricted throat the tube should taper outward at an angle of approximately 4 per cent.

A burner of recent design in respect to its Bunsen tube is an upright burner with a distributing head that directs the gas-air streams downward to attached small mantles in the rag form (Fig. 15). This is a small compact burner of high efficiency which may be included within the limits of artistic glassware. It possesses the advantages of upright burner performance while its compactness suits it to artistic treatment in lighting fixtures. The mantles used are of the inverted form and give a favorable distribution of light in a semi-indirect manner. This burner, being an efficient entrainer, obviates the necessity of using draft-inducing chimneys or cylinders.

Mantles operated in an inverted position possess marked advantages

over those whose position is upright. In the case of the latter, there is expansion and contraction due to heating and cooling, which tends to fracture the mantle by reason of the attachment to a fixed support above and sliding resistance on the burner cap below.

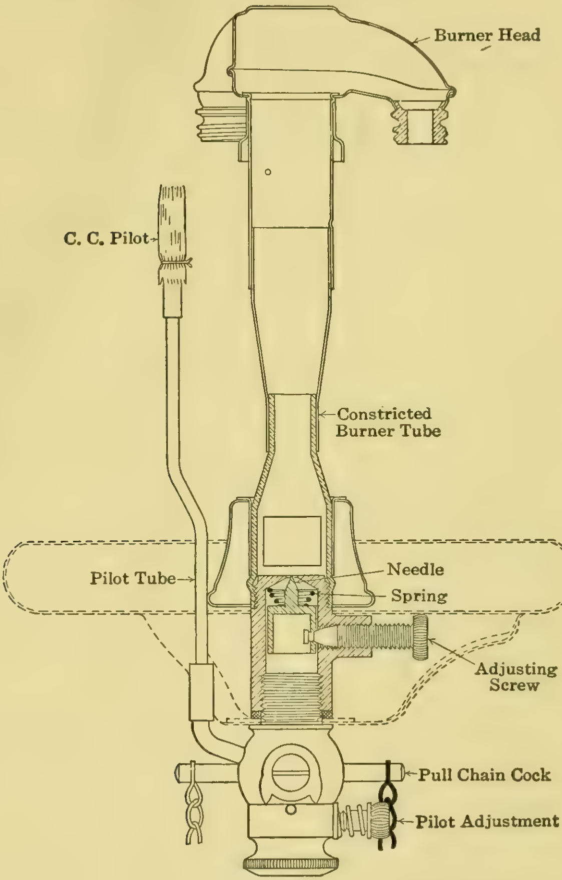


FIG. 15. Diagrammatic Sketch of an Improved Burner.

Another recently designed upright burner, constructed in accordance with the principles outlined, has a rather remarkable performance. A single upright mantle, mounted on a cap furnished with a gauze, is placed in position by slipping the gauze cap over the burner head. A mantle in the rag form is folded in a peculiar way so that when the fabric is burned out there is sufficient rigidity in the ash concentration to hold the structure in position until gas is turned on. A mild explosion shapes it into a beehive form and hardens it *in situ*. Clippings of

the web at four corners of the foldings give to the shaped mantles ventilating outlets near the top. These outlets reduce the pressure of the mixed gases and thus lessen the resistance offered to entrainment, with the result that this burner supplies to the mixture a larger proportion of air than any other form of burner in use. A very high oxygen content results in an extraordinary brilliancy of incandescence.

The specific brilliancy per unit of surface exceeds that of any other burner known, with the exception of burners that are designed to operate with high-pressure gas or air. The striking feature of this device, however, is its automatic adaptation to changes in gas pressure, due to the provision of overflow outlets at the top of the mantle. This obviates any necessity for needle control at the orifice or air-shutter adjustment. The parts of this burner are merely a Bunsen base, a properly designed Bunsen tube, and a gauze cap bearing a mantle. The whole structure is only about 3 inches long. The two lamps just described have a light output of 150 to 225 lumens per cubic foot of gas of 550 B.t.u. value delivered at a pressure of 3 inches (water column). Increase of pressure results in a marked gain of lumen output.

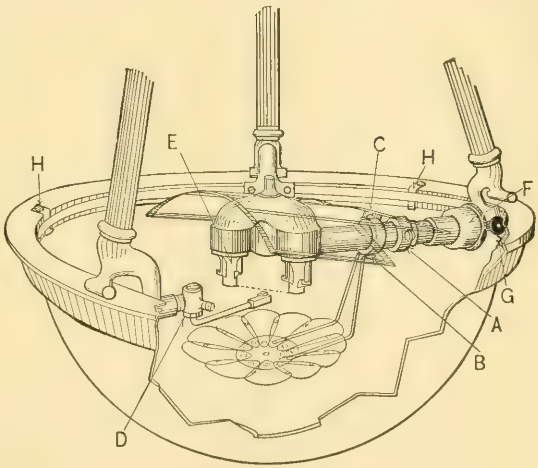


Fig. 16. Diagrammatic Sketch of Burner with Horizontal Bunsen Tube.

Such results are the best that can be produced on low-pressure burners, while those of inferior construction, popularly designated as "cheap," have hardly half this lumen output.

Higher gas pressures, say 2 pounds per square inch, give an efficiency about twice those of low-pressure burners, but this efficiency is given at the expense of complicated pressure appliances and short life of the mantle. CeO_2 volatilizes at high temperature, and a mantle consequently loses in efficiency. However, high-pressure lamps are used extensively a broad for street lighting, with remarkably pleasing effect.

One of the most valuable contributions to the gas-lighting art during the last few years has been due to the development of a burner whose Bunsen tube lies in a horizontal position (Fig. 16) and thus is adapted

to operation in a suspended bowl. One of the hollow suspension arms serves as a gas distributor from the outlet on which the structure is suspended.

The manifold has multiple outlets for mounting a group of burner tips and mantles and all are supplied with the mixture from a common Bunsen tube. The horizontal position of the burner structure permits it to be wholly concealed within the bowl. The light given out in this form of lighting device is distributed in a most pleasing semi-indirect fashion, part being distributed through the translucent bowl and another part by reflection from the bowl to the ceiling and thence by diffusion to parts of the room.

Atmospheric Vitiation. — When used in a home for which ventilation has not been carefully provided, gas flames may become a menace by removing the oxygen of the air. Column II, Table VII, containing illuminating values per liter of end products for various fuels, is of interest here. Assuming the practical equivalence of sperm and paraffin candles, it shows that each standard paraffin candle, for each hour of burning in a room, effectively removes the oxygen from $\frac{1}{.0115}$ or 90 liters (roughly 3.2 cu. ft.) of atmosphere. Certain experiments have shown that an active adult man consumes oxygen through respiration at the rate of 1100 liters per day, an average vitiation of atmosphere (20.90 per cent) of about 220 liters per hour, about $2\frac{1}{2}$ times that of a candle.

The data of Table VIII were obtained by comparing, from this viewpoint, various gas-flame sources.

TABLE VIII

Atmospheric Vitiation Due to Certain Light Sources

Sources	Candle-power	Vitiation Rate	$\frac{\text{Vitiation due to light source}}{\text{Vitiation due to active adult}}$
Candles..........	16	1140 liters per hr	6.5
Kerosene lamp....	16	550 " " "	2.5
Coal gas..........	16	920 " " "	4.2
Coal gas (Mantle burner)	16	155 " " "	0.7

Arc Lamps

[W. R. Mott]

Table IX gives a few of the important facts in the history of lighting by means of arcs.

TABLE IX

IMPORTANT FACTS IN THE HISTORY OF ARC LIGHTING

Discovery or Invention	Discoverer or Inventor	Date	Place
Carbon arc discovered	Sir Humphry Davy	1801	England
The name "Arc" first applied	Sir Humphry Davy	1821	England
Open carbon-arc lamp	Brush	1876	U. S. A.
Enclosed carbon-arc lamp	Marks	1893	U. S. A.
Yellow-flame carbon-arc lamp	Bremer	1899	Germany
Mercury-vapor arc lamp	Cooper and Hewitt	1901	U. S. A.
Vertical-flame arc lamp	Blondel	1902	France
Magnetite (oxide) arc lamp	C. P. Steinmetz	1900	U. S. A.
Enclosed-flame arc lamp	A. D. Jones	1908	England
White-flame photographic arc lamp	Norman Macbeth	1910	U. S. A.
High-intensity searchlight lamp	Beck and Sperry	1914	Germany and U. S. A.

It is interesting to note that about half of the important inventions in arc lighting were made in the United States.

Open Carbon Arc. — The discovery of the arc was made by Sir Humphry Davy over a century ago with the powerful electrical batteries newly installed at the Royal Institution. When two charcoal electrodes were placed together and then drawn apart, these batteries forced a heavy current through the gas separating the two electrodes. This hot, bright discharge took a bow-shape with horizontal electrodes and hence Davy called the phenomenon an " arc."

The practical development of the open carbon arc for street lighting was first carried out by Charles F. Brush. Considerable effort was made to increase the life of the carbons by coating them with metal, by using larger and longer carbons, by using magazine arc lamps holding two or more pairs of carbons, and by enclosing the arc to prevent the rapid oxidation of the electrodes.

Enclosed Carbon Arc. — The enclosed arc lamp decreased the rate of consumption of the carbons to about one-tenth that of the open carbon-arc lamp. A complete enclosure is impractical, because the carbon vapors must be burned at least to the carbon monoxide stage at the edges of the arc; otherwise, the carbon dust will blacken the glass globe. With the first enclosed arc lamps made by Marks, there was a valve to regulate the small amount of air entering the arc globe. However, modern carbons are so exact in size that sufficient air enters the globe between the upper carbon and the sleeve. It is important to note that the enclosed arc lamp was not used abroad for street lighting, because of its very poor efficiency compared with the open carbon arc.

However, the enclosure of the arc increased the proportion of ultra-violet radiation and so greatly enhanced its value for photochemical uses.

Flame Carbon Arc. — The investigation of the flame arc by incorporation of special chemicals in the electrodes was first made by Weston. The development of this idea was much more rapid in Europe than in the United States, because of the greater demand abroad for high efficiency in light production.

Many experiments with all kinds of materials and arrangements of electrodes, which led to the revolutionary flame-arc lamp, were made by Hugo Bremer. The two principal factors that made Bremer's lamp successful were (1) the inclined-trim or V-arrangement of the carbons, allowing the insulating slag buttons to drop off without interfering with arc operations, and (2) the discovery of mixtures of alkali silicates, borates and calcium fluoride that " wet " carbon. The use of these mixtures allows the molten flame material to be fed to the arc in an even way, similar to the action of a wick. The discovery of the value of calcium fluoride was very fortunate, as it has an intensely bright spectrum peculiar to itself. At first Bremer used solid impregnated flame carbons but this was soon given up for very small, long, cored carbons. The cored carbons allowed the chemicals to be vaporized directly into the center of the arc, and this materially increased the efficiency. The efficiency of these yellow-flame lamps per arc watt was about three times as great as that of the direct-current open carbon arc, and about ten times as great as the enclosed carbon arc on alternating current. Scores of different types of flame lamps were developed after Bremer's work. They found an extensive use for advertising and for the illumination of large spaces.

The next step in the evolution of the open carbon flame-arc lamp was the change from the inclined trim or V-shaped position of the carbons to a vertical alignment of the carbons which gave a light distribution ideal for street lighting.

The enclosure of the flame arc was made by A. D. Jones, who employed cored flame carbons. This was followed by the development of solid flame carbons which were employed in enclosed flame-arc lamps for street and factory lighting.

Magnetite Arc. — The magnetite arc represents the utilization of oxides for an electrode, which allows a long life under open-arc conditions.

General Applications. — The usual characteristics of arcs that are of special value for illumination are efficiency, ruggedness, adjustability, concentration of light source, and the control of the color of light. The necessity of trimming and the presence of undesirable products of

combustion are two objections to them. The complicated mechanism is also a handicap in comparison with simple convenient units such as incandescent lamps. The result has been that the arc is largely confined to large-wattage units for outdoor illumination, to projection uses (because of its superlative crater brightness), and to photochemical uses where high efficiency in producing blue and violet light is necessary.

The Arc Defined. — The exact definition of an arc has been the source of some confusion because of the many kinds of arcs and their similarity to other forms of electrical discharge, such as the electric spark and the brush discharge. After careful consideration of the many aspects of the arc, the following definition is proposed: **An arc is a column of very hot and highly conducting vapors carrying a current sustaining this condition.**

The vapors may be furnished by either electrode or by the atmosphere. Solid conductors, liquid electrolytes, and hot conducting oxides have been used as electrodes. In regard to current values, arcs range from a fraction of an ampere to many thousand amperes. The arc voltage is much lower than that of sparks and of most of the vacuum cathode discharges. In distinction from the spark, the arc has sufficient energy to sustain the conducting state. The columnar shape of the arc is a result of its indivisibility. This is a distinction from the brush discharge.

An arc has its conductivity increased by increased current. The heat produced by the increased dissipation of energy in the arc with increased current causes the conductivity of the gases between the electrodes to become greater and decreases the voltage drop between the electrodes. Hence, it must have an external resistance (or other apparatus such as a limiting reactance on alternating current circuits) in series with it in order to prevent its indefinite expansion to what is called a short-circuit arc.

The electrical conductivity of hot gases increases very rapidly with temperature. This not only causes an arc to hold together in one column but also explains other peculiarities, such as its volt-ampere curve. Solid electrolytes on heating show similar effects, as is illustrated by the Nernst lamp.

Appearance of Arcs. — The direct-current arc has been described as consisting of a very large, hollow, positive crater and a much smaller negative crater. The arc itself has a violet core and a green or greenish-yellow shell. This arc shell is due to impurities consisting of alumina, iron and boric oxide in the coke of which the carbons were made. By the use of much purer carbons and higher currents, the shell becomes very dim. Fig. 17 is a photograph of a flame arc in black and white.

On the other hand, the addition of chemicals to the carbon changes

the color and brightness of both the core and the shell of the arc. The yellow-flame arc, made with calcium fluoride, gives a violet core and a very bright yellow shell. The red-flame arc, made with strontium fluoride, has a blue core and a red shell. The white-flame arc, made with a rare-earth fluoride, has an intensely blue core and a less well-defined shell, with the inner part somewhat green and the outer part somewhat red.

FIG. 17. Photograph in Black and White of a Flame Arc.

Since almost any material which is introduced into the arc causes some unique behavior, it has been proposed to use the arc for chemical analysis.

Classes of Arcs. — Arcs may be divided into two major classes: (*a*) crater arcs, and (*b*) luminescent arcs.

The crater of a crater-arc is the hot surface at the electrode tip from which the arc stream originates. Most of the light of a crater or neutral arc is emitted from its craters. The positive crater of a direct-current carbon arc gives about 90 per cent of the light, the negative crater and the arc stream the balance. The reason that the positive crater gives the most light is that here the most energy is liberated. The anode drop is large, usually about 40 volts; the cathode drop is less than 10 volts, and the balance is in the arc stream. As the power of carbon vapors to give visible light is very small, the energy expended in the arc stream is largely wasted. The reverse is the case with the luminescent arcs, including the flame-arcs.

Luminescent arcs may be defined as those which give considerable light from the arc stream in addition to that from the craters.

To the crater arcs belong the open carbon arc, the enclosed carbon arc and oxide arcs. To the luminescent arcs belong the flame carbon arcs, the magnetite arcs, the mercury-vapor arcs and the tungsten arc in vapors of titanium chloride at reduced pressures.

Principal Factors Governing Arc Output and Operations. — The amount and quality of light from an arc will depend upon a great variety

of conditions, such as (1) the chemical composition of the electrodes; (2) the chemical composition, motion and pressure of the atmosphere around the arc; (3) the kind and amount of current and the voltage across the arc; (4) the magnetic field in and around the arc; (5) the nature of the ballast in series with the arc.

Chemical Composition of the Electrodes. — The chemical composition of the electrode determines the brightness of the anode crater and the spectrum nature of the light of the arc stream. Only materials having the highest boiling points, such as carbon, zirconium oxide, tantalum and tungsten, are suitable when the light is to be produced by the brightness of the craters on the electrodes.

With flaming arcs, the flame materials are carried from the anode to the cathode when a current of less than 50 amperes is employed. The inclined-trim carbons are usually made with flame material in the positive electrode only, because its high heat is sufficient to fill the arc with the light-giving vapors. Putting the flame material in the negative electrode in this case may add only 10 per cent to the light.

The magnetite arc is especially distinguished from the plain carbon arc and the flame arc in that its anode is comparatively cold, being made of massive copper. The cathode is composed of magnetite (electrically conducting oxide of iron), titanium oxide which is the best light giver in these arcs, chromium oxide which decreases and regulates vaporization, and alkali salts for improving the arc conductivity. All these materials are compressed in a thin-walled iron tube. While in the case of the flame arc, the salts are carried into the arc by vaporization from the anode, in the magnetite arc the materials are carried into the arc by vaporization from the cathode.

With regard to the amount of light-giving material that can be used in an arc, doubling the amount of material does not necessarily double the light, but the increase is more apt to be about 25 to 50 per cent.

An upper limit is reached in the use of large amounts of flame material, because of (1) the increased energy required to boil the greater amount of material; (2) increased cooling effect on the arc stream; and (3) the increased obstruction of light by the condensation of the flame vapors as a dust around the arc. In general, the enclosed flame arc (employing large, solid, impregnated carbons) uses twice as much flame material per ampere-hour as the open flame arc employing small, cored carbons. In spite of the smaller amount of flame material, the candle-power of the cored carbons is generally better than that of the solid flame carbons, because of the adverse effect of enclosing the arc and the greater heat losses by conduction with the large. solid flame carbon.

Data obtained with calcium fluoride in cored carbons have been reduced to the following equation:

$$E = 2.18 + 6.8 \log \frac{c}{4}$$

where E is the mean lower hemispherical candlepower per arc watt and c is the per cent of calcium fluoride in the core of the positive carbon (8 mm. diameter). Table X shows that the observed and calculated efficiencies of light production check closely.

TABLE X

EFFICIENCY IN RELATION TO AMOUNT OF FLAME MATERIAL

Per Cent of Calcium Fluoride	Mean Lower Hemispherical Candlepower	Calculated E	Observed E
0	1173	....	....
8	1728	4.22	4.32
15	2505	6.20	6.17
20	2808	6.94	6.95
25	3268	....	....
30	3321	8.10	8.20
35	3385	....	....
40	3574	8.98	8.85

A similar type of equation appears to apply broadly up to the limit at which the energy required for the evaporation of the flame materials becomes excessive. The electrical conductivity of the materials in the region near the crater also becomes important in limiting the amount that can be used. Aside from these limitations, the general form of the equation of the efficiency, E, of the production of light to the amount of concentration, c, of the flame material is as follows:

$$E = K_1 + K_2 \log \frac{c}{K_3}.$$

With each material, experiments are necessary to determine the proper values of the constants, K_1, K_2 and K_3. A study of the nature of these equations shows that mixtures of several materials might increase the efficiency and this is substantiated by experiment. The above results check so well as to suggest that the form of the equation has more than an empirical meaning. Since absorption of light can be expressed as a logarithmic function of the amount of the material, it is to be expected that the emission of light would also be a logarithmic function of the amount of the material.

Effect of Surrounding Atmosphere. — Air currents decrease the arc steadiness and cause more voltage to be required in the arc ballast. A strong air current will blow out the arc. The vapors of the arc itself have a number of motions: (1) the general movement from anode to cathode of the carbon arc; (2) a rapid circulatory motion; (3) a rapid expansion and contraction in the case of the hissing or talking arc. In the case of a flame arc, the upward rush of hot air about doubles the efficiency for producing light when the flame material is fed only from a lower positive flame carbon as compared with an upper positive flame carbon. If both carbons are of flame composition, then the positive upper may give as much light or even more than the positive lower.

The chemical composition of the atmosphere around the arc affects its light materially. An extreme case is found in the arc consisting of tungsten operating in low-pressure vapors such as titanium chloride. Here the tungsten electrodes contribute no material light-giving vapors, but the atmosphere feeds the arc with light-giving chemicals. With the carbon arc, enclosure increases the photographic light many times because the cyanogen of the arc is less quickly burned in the presence of an atmosphere rich in carbon monoxide. With the flame arcs, especially those giving light by chemical reaction in the arc shell, an enclosure causes a considerable decrease in the amount of light. When calcium fluoride is used in the open flame arc, considerable light comes from the spectrum of the calcium oxide formed, which is materially decreased by enclosing the arc. It is, therefore, necessary for the production of high intensity of light with this material, under enclosed arc conditions, to add materials containing oxygen, such as alkali carbonates, borates and tungstates.

As the arc is composed of hot vapors, it is considerably affected by the mechanical pressure of the surrounding gases. A decrease in the pressure causes the arc to expand and become less bright in temperature. It is obvious that if the anode material is held at its boiling point, an increase in the pressure should (1) increase the amount of energy necessary at the crater surface in order to reach the higher boiling point and (2) therefore, increase the crater brightness.

The Effect of a Magnetic Field. — The arc is deflected by a magnetic field in the direction in which a flexible conductor would be deflected if it carried a current flowing in the same direction as that through the arc. With two parallel conductors, the magnetic action of the arc current drives the arc to the ends of the electrodes. This magnetic force is so great that the arc can be operated at the lower end of a V-trim of carbons in spite of the upward push of the hot-air currents around it. A magnetic field formed by electromagnets operated by the current

in series with the arc is used in inclined-trim lamps in order to flatten the volt-ampere curve and thus to decrease the ballast that is necessary and hence to increase the overall efficiency for producing light. On the other hand, in lamps with a vertical trim, a special effort is made to avoid the magnetic effect of the current going to the lower carbon, by exactly dividing the current between the two oppositely placed conductors. The shape of the lower holder has a considerable effect on the magnetic field surrounding the arc. It can be truly said that the success or failure of many arc lamps has rested on the care taken to eliminate or regulate the magnetic effects.

Consumption of the Electrodes. — The consumption of the electrodes in an arc lamp depends on oxidation and volatilization. With the carbon electrodes, oxidation is the chief factor, as contrasted with the volatilization of magnetite electrodes. Table XI will give a general idea of the rate of consumption per hour of the two electrodes that together constitute a trim.

TABLE XI

RATE OF CONSUMPTION OF ELECTRODES PER HOUR

Current Type of Arc	Electrode Diameter	Arc Current	Arc Voltage	MM. per Hour
D. C. Open Carbon Arc	$\frac{5}{8}''$	9	40	16 mm.
D. C. Open Flame Carbon Arc	$\frac{3}{8}''$	10	45	30 "
A. C. Enclosed Arc	$\frac{1}{2}''$	6.6	70	1 to 2 "
D. C. Magnetite Arc	$\frac{5}{8}''$	3.5	91	1 to 2 "
A. C. Enclosed Flame Arc	$\frac{7}{8}''$	10	45	2 to 3 "

In general, the consumption of the positive carbon is about twice that of the negative, because of the greater heating effect of the large positive crater. The consumption of both carbons increases with the current. While the lower carbon is not particularly affected, the upper carbon burns more rapidly with increasing arc voltage. An enclosure reduces the rate of consumption of the carbons, so that the life is increased five to twenty-fold under like conditions.

With short, protected carbon arcs, the anode crater loses carbon and the cathode crater takes up a mushroom deposit of carbon. Arcs so short as to give mushroom deposits are unsuitable for lighting.

Color Resources of the Arc. — As the sun gives a color temperature of about 6500° K., and the positive-carbon arc a color temperature of about 3700° K., it can readily be seen why the light of the arc is more yellow in color. The alternating-current carbon arc is more yellow than

the direct-current arc because of the lower average temperature of the craters, as each crater is a positive only half of the time.

The addition of chemicals to the arc greatly extends the range of colors obtainable. By means of mixtures, many gradations of colors can be obtained. In Table XII, the best materials for producing various colors are given.

TABLE XII

COLOR OF LIGHT IN RELATION TO MATERIAL IN THE ARC

Color of Light	Material in the Arc
Red	Strontium, yttrium
Yellow	Calcium fluoride
Green	Erbium, thallium, mercury
Blue-white	Rare earths, uranium, iron, titanium
Ultra-violet	Uranium, iron, mercury

The yellow-flame arc is about the color of the old incandescent carbon-filament lamp. A combination of yellow-flame materials and blue-white materials gives a color of light that is used for the illumination of streets. For want of a better name, it has been called pearl white. For photographic work and the matching of colors, the blue-whites are chiefly used. They give a color which is nearly as blue-white as northern daylight. The red-flame carbons are used mainly for advertising purposes.

In the matter of ultra-violet for medical purposes, sterilization, etc., the iron arc is quite rich in both the near and extreme ultra-violet. The uranium arc is much more powerful than the iron arc. For ultra-violet light of the same type as that in sunlight (0.380μ to 0.300μ), the white-flame arc is the best source.

Temperature, Brightness and Area of Arc Craters. — A method of changing the brightness and temperature of a crater is by changing the atmospheric pressure on the arc, which would in turn change the boiling point. In regard to the carbon arc, brightness and temperature measurements with increased and decreased pressure are set forth in Table XIII.

TABLE XIII

EFFECT OF REDUCED PRESSURES ON ANODE CRATER BRIGHTNESS AND TEMPERATURE OF A PURE CARBON ARC

Pressure, atmospheres	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.1
Relative brightness	1.0	0.99	0.97	0.95	0.92	0.88	0.83	0.59
Absolute temperature	4200	4195	4185	4175	4160	4145	4110	3940

Effect of Increased Pressures on Anode Crater Brightness and Temperature Using a Solid Flame Carbon

Pressure, atmospheres	1	2	4	8	12	16	22
Relative brightness	1.0	2.5	4.4	7.8	11.0	14.2	18.0
Absolute temperature	4200	4690	5000	5350	5560	5740	5890

The above table shows that by increasing the pressure from 1 to 22 atmospheres, the crater brightness is increased eighteen-fold.

The temperature and brightness of either crater has an upper limit which is the boiling point of the electrode material. With metal arcs, it is possible to have cold anodes, because the arc feeds its conducting material from the hot negative spot. In these metal arcs, the temperature of the crater is believed to reach the boiling point of the negative electrode material. However, with very high boiling-point materials, the positive electrode feeds the arc with its vapors and in this case the limit of the temperature of the positive crater becomes the boiling point (or sublimation point) of the anode material, and the negative crater may be several hundred degrees cooler than the positive crater. Arcs with very hot positive craters are those of carbon, zirconium oxide and tantalum (boiling point 5500° C.). The crater brightness and boiling-point temperature of several materials, such as tantalum, are much higher than those of carbon itself.

Materials having boiling points lower than the sublimation temperature of carbon reduce the brightness and temperature of the positive crater, when incorporated in the carbon. Materials boiling above the sublimation temperature of carbon have positive craters that are hotter than that of the carbon arc. The crater area is much reduced and the energy density may be several times that obtained with the carbon alone. The crater brightness and temperature are especially high with a large tantalum bead (1/2 gr.) in a lower positive carbon cup with a direct current of 25 amperes. Therefore, in addition to increased pressure for securing brilliancy and high temperature of craters, a second method involves the use of materials with boiling points higher than the sublimation temperature of carbon.

A third method of securing very high temperatures (approximating that of the sun and much higher than a pure carbon arc) is by means of the so-called high-intensity searchlight arc, in which very high current density is concentrated upon a small volume of luminescent vapor in a small crater cup at the end of the flame positive electrode. The brightness of this vapor corresponds to 690 candles per sq. mm., while the solid carbon gives 172 candles and the neutral cored carbon 130 candles per sq. mm.

The negative crater of the usual carbon arc is about 600° cooler

than the positive crater. The temperature and brightness are not constant as in the case of the positive crater of a carbon arc. The area is less and the brightness is less; hence the total light produced from the negative crater is very small compared with that from the positive crater.

The chief effect of the negative crater on the carbon arc is to control steadiness, and to insure this latter condition the negative crater must always be hot enough for abundant electron emission. No arc can be maintained where the negative electrode is subjected to violent cooling effects, as by rapid motion through the atmosphere.

Crater Area and Light in Relation to Current. — As the chief light source of a pure carbon arc is the positive crater, this crater area is a variable of great importance in illuminating engineering. The crater area depends on the composition and size of the electrodes, the current, the arc length, and the chemicals in the arc.

It has been shown that with solid carbons the crater area increases 2.4 times when the current is doubled. This relation holds over a wide range of searchlight and motion-picture projectors, employing carbons of the proper size for each current. However, it would be a gross error to say that the light of carbon arcs is limited to direct proportionality with the current used. With flame arcs the light increases still faster when the current is increased than with the pure carbon arc.

Spectrum Nature of Arc Light. — All three kinds of spectra — continuous, band and line — are given by a flame carbon arc. The craters have the continuous spectra so characteristic of hot solids. The core of the arc gives line spectra, and the shell of the arc, band spectra. The band spectra under a high resolving power are seen to be really made up of closely packed lines with regular changes of spacing between them. Compounds giving band spectra in the carbon arc are calcium fluoride, strontium fluoride, barium fluoride, barium chloride, beryllium fluoride, and most of the refractory oxides, such as alkaline earths, boric oxide, aluminum oxide, yttrium oxide, etc. Of the carbon compounds, the most important band spectrum is that due to cyanogen $(CN)_2$.

The shell of the yellow-flame arc containing calcium fluoride gives intensely bright bands in the red and green portions of the spectrum. Calcium oxide gives very intense bands in the red. Thus the yellow of the yellow-flame arc does not come from the yellow part of the spectrum. Strontium fluoride gives intensely bright yellow bands and, owing to the presence of oxide formed by decomposition, the red bands are also very bright.

The white-flame arcs owe most of their light to the thousands of

light-giving lines in all parts of their spectra. This is illustrated in Fig. 18.

These line spectra belong to the elements.

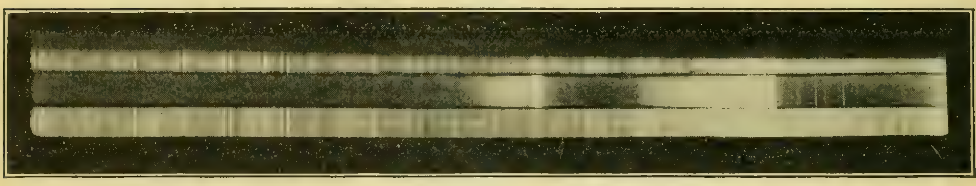


FIG. 18. Spectra — Outer Two, Snow-white Flame Arc; Inner, Pure Carbon Arc.

Electroluminescence of the Arc Core. — The laws of radiation of hot solids apply to the light from the crater and to the zones of lower temperature around the crater. Flame materials in the core of an alternating-current carbon arc give light in almost exact synchronism with the instantaneous current value and may thus be put in the electroluminescent class.

In the carbon arc, the poorest emitters of light are the non-metallic elements, such as sulphur. They are also poor arc conductors. Both of these effects are explained by the extreme difficulty of pulling electrons from non-metallic atoms. The metals that lose electrons most easily are the alkalies. These, in minute amounts and at low temperatures, as in the Bunsen flame, are wonderful emitters of light, but they are very poor at arc temperatures. Elements of groups having a high valence and increasing atomic weight give a maximum of lines and respond most to the current effects in the arc core, resulting in a high efficiency of light production. This is particularly true of titanium, vanadium, chromium, iron, rare earths and especially uranium. The importance of core light is that it responds to the current density and utilizes the electrical energy of the arc stream, which is practically wasted in the ordinary pure carbon arc. The production of light by materials giving a luminescent core increases about as the square of the current. The light of the white-flame arc is derived mostly from the core of the arc stream.

Chemiluminescence of the Arc Shell. — The yellow-flame arc gives almost all its light from the arc shell. Compounds having the greatest energy of formation (i.e., highest decomposition voltages) give the strongest and brightest arc shells with the smallest amounts of material and are most effective in producing arc light of extraordinary efficiency at low wattage. Direct-current arcs employing but 2 to 4 amperes

can be made remarkably efficient by using materials giving bright arc shells.

It is interesting to note that arc shells in relation to arc cores always have a dominant color of longer wave-length. With a given compound giving an arc core and inner and outer arc shells, the order of color is always violet or blue for the core, green for the inner shell, and red for the outer. Arcs are not found with a blue shell or with a red core.

Fluorescence. — The maximum of ultra-violet light is produced in the core of the arc. Ultra-violet light of extremely short wave-lengths probably plays an important part in the production of light through its transformation in the outer parts of the arc shell to longer wave-lengths, thus producing light by fluorescence.

Arc Conductivity — Importance of the Hot Negative Spot. — The explanation of the phenomena connected with the discharge of electricity from incandescent bodies explains very simply the behavior of the negative electrode in an arc. With the ordinary carbon arc, the cathode spot corresponds to a current density of only about 318 amperes per sq. cm., but with the 150-ampere high-intensity searchlights, the current density at the cathode crater is 8000 amperes per sq. cm. The difficulty of getting a still greater current density lies in the specific resistance of the electrode material and that of the vapor in front of the cathode crater.

For good stability of the arc, it is important to conserve the highest temperature of the cathode. A sharp-pointed negative gives this condition. The carbon arc is the most stable of all arcs that operate on alternating current, because of the high temperature of the sublimation of carbon and the low thermal conductivity, and also because the flow of arc vapors, unlike that of the metallic arcs, is from the hotter positive crater to the negative crater spot, which is thereby heated. The stability of the carbon arc is greatly improved by the introduction of flame chemicals which reduce wave distortion and improve the power factor. The temperature of the negative spot and hence arc stability are improved by large current and high frequency.

Conductivity of Arc Vapors. — The conductivity of arc vapors increases very rapidly with the temperature. This is one of the factors that tend to force the current toward the center of the arc and thereby further increase its temperature and conductivity. The electrical conductivity of elements in the arc depends largely on the ease with which they give off electrons. In carbon arcs, it is common to use alkali salts, which are called arc supporters, for the sole purpose of improving the arc steadiness and the ease of its control.

Relation of Arc Voltage to Arc Length. — The relation of arc voltage to arc length is that of a linear function. Each added unit of arc length requires like increase in the arc voltage, provided the initial voltage is high enough to start the arc. There is a minimum voltage, however, below which the arc is inoperative; this is called the "starting arc voltage." The starting arc voltage of the carbon arc is about 40 volts, while that of the flame arc is half this value. The flame-arc stream of the flame arc requires a half to a third as much voltage per unit length as that of the pure carbon arc. These facts are shown graphically in Fig. 19. The great increase in the length of the flame arc over the pure

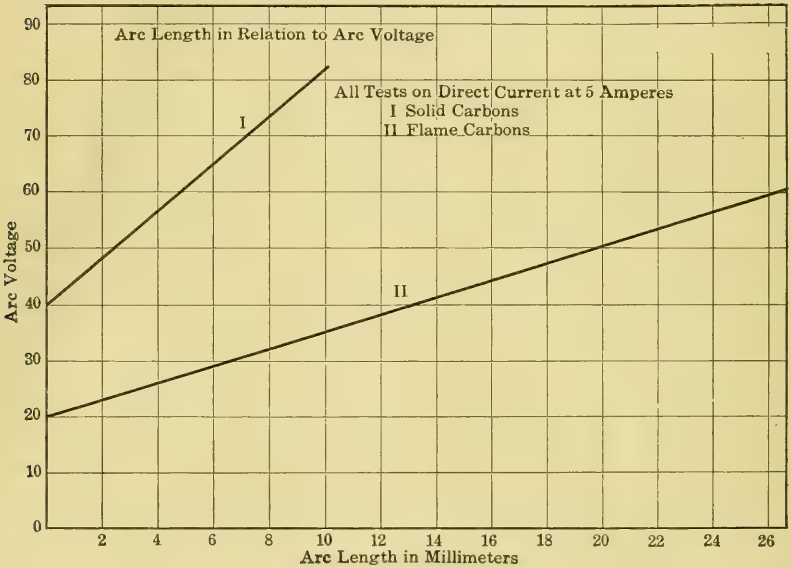


FIG. 19. Arc Length in Relation to Arc Voltage for a Carbon Arc and a Flame Arc.

carbon arc makes it less sensitive to mechanical deficiencies in the drawing of the arc. Arc-lamp design and manufacture are made easier. This applies to both arc feeding and general operation.

If the current is increased, then the arc voltage for a fixed length correspondingly decreases, as is shown in Fig. 20. The energy in the arc increases, however, and hence the heating effect increases.

Power-factor. — On alternating current, the volt-ampere curve causes a wave distortion and a decreased power-factor, especially on low frequencies. The flame carbon arc shows these effects the least of any type of arc. Referring to the instantaneous-voltage curve, the

first condition that appears with the alternating-current arc is that the starting arc voltage must be reached before the current will flow. The second condition is that at the maximum of current the actual voltage of the arc itself is relatively low at the moment of maximum voltage

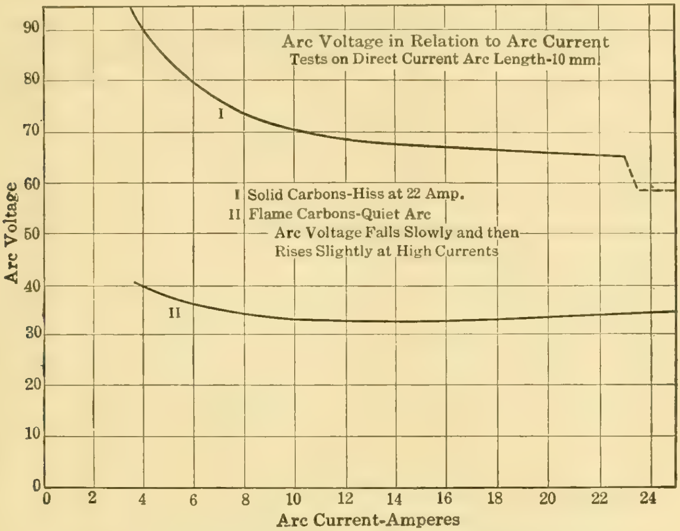


Fig. 20. Arc Voltage in Relation to Arc Current for a Carbon Arc and a Flame Arc.

of the line. This makes a complicated wave distortion and so causes a lower power-factor. Table XIV shows the power-factor of different arcs at 60 cycles per second.

TABLE XIV

Power-factor of Different Arcs

Kind of Arc	Power-factor
Magnetite arc	50%
Enclosed carbon arc	80%
10-Ampere flame arc	87%
25-Ampere white-flame arc	97%

Series Arrangement of Arcs. — The ideal circuit for arc lamps is the constant-current or series circuit, in which all the power can be utilized in the arcs themselves, as contrasted with multiple circuits which waste part of the power in arc ballast. In American cities, series circuits operating with several thousand volts are common, while in Europe the multiple arrangement of arc lamps predominates.

In the following table, there are shown typical arc lamps used on

series circuits. The carbon arc lamp is the only one in use on alternating-current circuits. The low voltage of the arc has the advantage of increasing the number of lamps per series circuit of fixed voltage.

TABLE XV

ARC LAMPS USED ON SERIES CIRCUITS

Lamp	Current	Volts	Lamps per 1000 Volts
Open carbon arc d.c.....	9.6	50	20
Enclosed arc a.c.........	7.5	72	14
Flame arc a.c...........	10	50	20
Magnetite d.c...........	4	80	12.5

Multiple Arrangement of Arcs. — The multiple arrangement of arcs for street lighting has been extensively used in Europe with flame arcs but has not been developed in America. The objection to the multiple arrangement is the increased loss of energy used in the ballast of the arc lamps. Data on this are given in the following table for 110-volt circuits.

TABLE XVI

VOLTAGE DISTRIBUTION ON 110-VOLT CIRCUITS

Type of Arc Lamp	Total Arc Voltage	Ballast Voltage
Open type of carbon arc.......	50	60
Enclosed arc..................	72	38
Single-flame arc..............	60	50
Open twin-flame arcs.........	90	20

On 220-volt circuits, the relations are shown in Table XVII.

TABLE XVII

VOLTAGE DISTRIBUTION ON 220-VOLT CIRCUITS

Type of Arc Lamp	Total Arc Voltage	Ballast Voltage
Enclosed arc (photographic) ..	120	100
Enclosed flame arc...........	120	100
Two-series flame arcs.........	120	100
Four-series flame arcs.........	180	40

Relation of Voltage to Efficiency. — The carbon arc has an abrupt increase to a maximum of light efficiency just above the starting arc

voltage, especially with small carbons. In contrast with this, the flame arc starts giving light at half the voltage of the carbon arc and continues to increase in efficiency to very high arc voltages. This difference in behavior is shown in Fig. 21. The chief benefit of a long carbon arc is to decrease the shadow caused by the lower carbon.

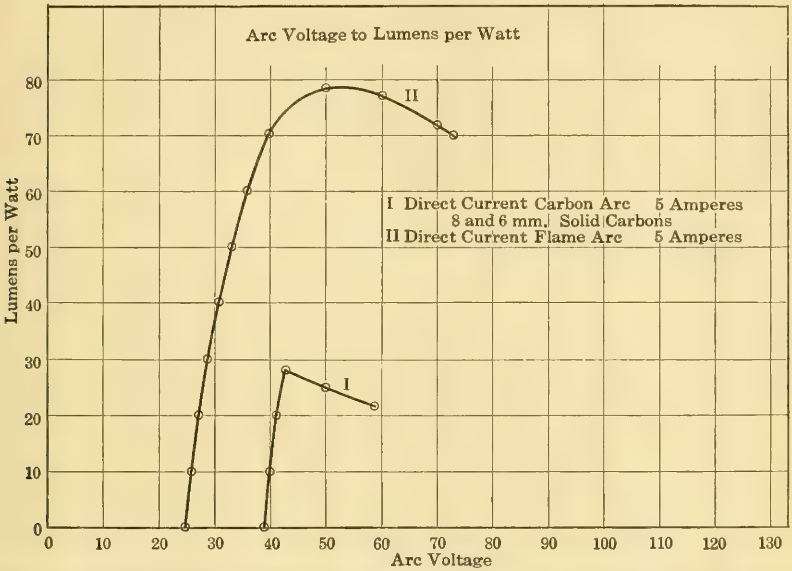


FIG. 21. Relation of Arc Voltage to Lumens-per-Watt for Carbon and Flame Arc.

With very high arc voltages (above 100), the light increases, but at a slower rate, because of (1) the cooling action of increased air currents; (2) the escape of the light-giving vapors from the arc; and (3) increased dust arising from the condensation of the arc vapors.

The relation of photographic light to arc voltage is shown in Fig. 22. By calculating efficiency, it is seen that in this case the maximum light per watt in the arc is at about 45 arc volts. This makes it possible to place two flame arcs in series on 110-volt circuits at their maximum of light efficiency. Two enclosed carbon arcs cannot be operated in series on a 110-volt circuit. This illustrates the electrical advantages of flame arc on both multiple and series circuits.

The voltage-power component of alternating current is very effectively utilized by the flame-arc stream but wasted in the pure carbon arc. The light efficiency of a pure carbon arc is nearly twice as great on direct current as on alternating, because of the greater heat losses at the craters of the latter. For the same reason, large, solid flame carbons also give slightly better efficiency on direct current. On the other hand, small

cored flame carbons give better efficiency on alternating current because of small heat losses at the craters. The voltage-power component and the feeding of the flame materials, from both electrodes, favor the light efficiency of alternating flame arcs. As a result of using small cored

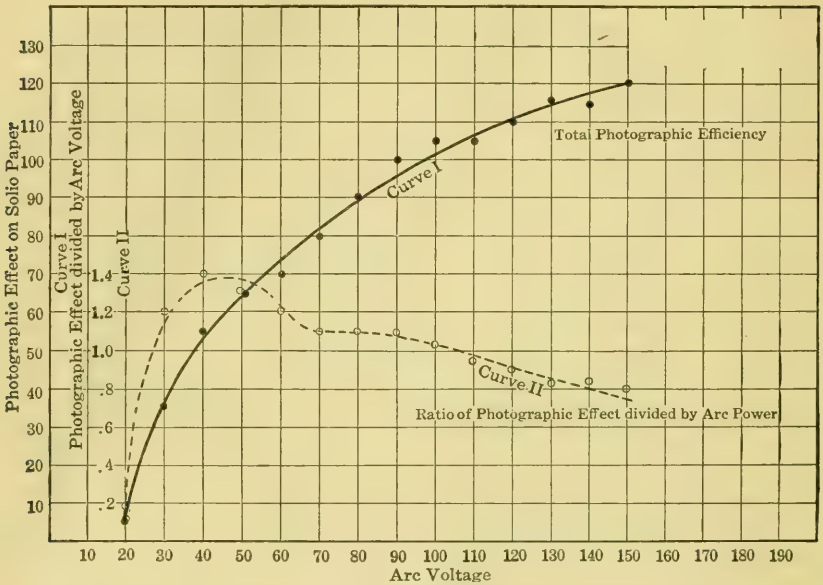


FIG. 22. Relation of Arc Voltage to Photographic Light.

carbons, the white-flame arc gives 50 to 100 per cent greater efficiency for photographic purposes on alternating than on direct current.

The conclusion is that the flame arc effectively utilizes a wide range of voltage conditions and has made possible a variety of new arc-lamp designs.

Relation of Current to Efficiency. — With the pure carbon arc, using the proper sizes of carbons on either direct or alternating current, the light increases with the current as the 1.4 power. With flame arcs, the visual light increases with the current to the 1.6 power. This exponent (1.6) also applies to the light from the magnetite arc. With flame arcs of the tungsten type, the data indicate that the light increases as the square of the current.

On direct current the photographic light increases as the current to the 1.8 power, while on alternating current the increase is approximately as the 2.2 power of the current.

The relation of the photographic power to the current is shown in Fig. 23. The relation of visual light to the current of a yellow-flame enclosed arc is shown in Fig. 24 in the form of light distribution curves.

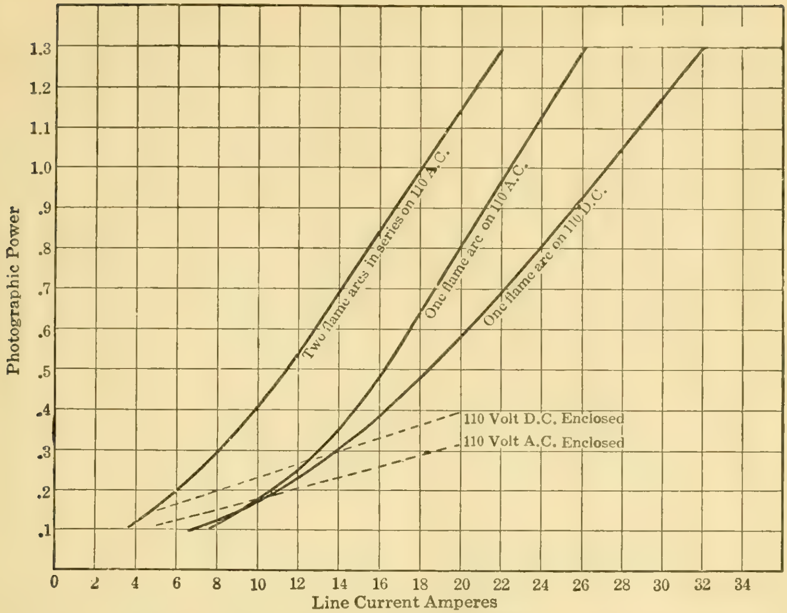


FIG. 23. Relation of Current to Photographic Effect on 110-volt Lines with Enclosed Carbon Arc Versus Single and Twin-flame Arcs.

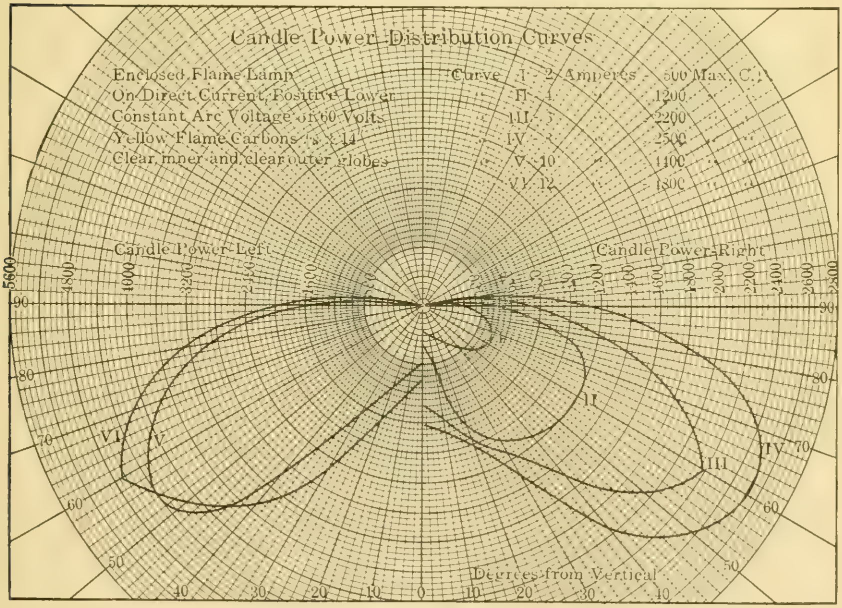


FIG. 24. Candlepower Distribution Curves with a Solid Flame Carbon Arc at Different Currents.

Importance of Arc Control. — Since the arc is characterized by a marked decrease of its resistance with an increase in current, the arc voltage also decreases. Hence, the maintenance of a stable arc depends very much upon the kind and amount of external resistance in series with it. This feature of the arc is an advantage from the standpoint of wide regulation but it is a disadvantage from the standpoint of the power lost externally to the arc in its current-regulating apparatus, called the arc ballast. On a multiple circuit, the arc ballast may consume 1 to 50 per cent of the total electrical energy used, depending on the kind of arc and ballast, while on a series circuit this loss is avoided, because of the constant current which is supplied by the generating apparatus.

Arc Ballast. — On direct current, the arc ballast is usually a resistance wire with a low temperature coefficient of resistance, so that as the resistance heats up, the arc regulation will not change. If the resistance is arranged on a magnetic core, the steadiness of the arc is improved.

On alternating-current circuits, reactance may be, and usually is, employed instead of the steadying resistance, and the waste of power is thereby greatly decreased. Of course, the power factor is less favorable with a reactance ballast. An important aspect in determining the kind of ballast which should be used in an arc is its effect on the efficiency of the arc itself. In the case of the carbon arc, the use of a reactance decreases slightly the lumens per arc watt. The exact reverse results with the flame arc. The use of a reactance with a flame arc gives a considerably higher efficiency of the arc itself than the use of a resistance ballast.

Globes. — The use of globes introduces two additional points of interest to the engineer: (1) the effect on the distribution of the light, and (2) the light absorbed (Table XVIII). Absorption of light by the globe has been a big problem in arc-lamp design because the mineral products or ash from the electrodes must be prevented from depositing on the globe and thereby obscuring the light. A great deal of investigation was necessary to show how this could be done in the long-life flame lamps where operation was required for 100 to 200 hours. A complete solution was found in a cooling chamber or circuit above the arc and a means of keeping the glass globe hot. The latter was accomplished by the simple device of using a second globe so that the air space between the two prevented the cooling of the inner globe. In all lamps equipped with glass, attention must be given to keeping this as clean as possible.

TABLE XVIII

EFFECT OF GLOBE ON LUMENS PER WATT OF LINE POWER

Description of Light Source	Lumens per Watt	
	No Globe	Fully Equipped
Series open-flame vertical lamp on d.c., 10-amp., 43-v., pearl-white carbons	120.0	100.0
Series open-flame vertical lamp on a.c., 10-amp., 35-v., pearl-white carbons	62.5	50.0
Multiple inclined-trim yellow-flame lamps on a.c. or d.c., 10 amp., 55-v., cored carbons		48.0
Series open-flame vertical lamp on d.c., 6.6-amp., Boston-type cored carbons		45.0
White-flame single arc lamp, multiple, 25-amp., 110-v., with resistance, snow-white carbons	29.0	
Series magnetite lamp, d.c., 6.6 amp		17.0
Long-burning enclosed flame arc lamp, series street lighting, white		17.0
Series open carbon arc lamp, d.c., 9-amp., 40-v	16.5	14.0
Series magnetite lamp, d.c., 4.0-amp	13.0	11.0
Gas-filled incandescent lamps of 300 watts, fully equipped for street lighting		9.5
Series enclosed carbon arc lamp, a.c., 6.6-amp		6.0
Multiple enclosed carbon arc lamp, a.c., 6.6-amp		4.0

The etching or corrosion of glass globes by American carbons was decreased by the use of zinc oxide and lithopone in the carbons as basic (acid-neutralizing) materials. A very efficient absorbent for the corrosive gases was discovered in fused boric oxide, which is now used in white-flame street lamps. The amount of material to be neutralized is only 0.003 gram per hour.

Operation for Street Lighting. — For the open carbon arc, from 4 to 25 lamps were operated in series on a 9.6-ampere direct-current circuit, with a 45-volt difference of potential between the electrodes of each lamp.

Higher arc voltages are necessary with enclosed than with open arc lamps, because of the increased resistance of the arc stream and because the electrodes need to be farther apart to allow the light to escape. The electrodes of the enclosed arc lamp burn with blunt, flattened ends which cause more shadowing of the light than is the case with the more pointed electrode tips of the open arc lamp. The most common types of enclosed arcs operate on alternating current at 6.6 to 7.5 amperes and 70 to 80 arc volts. The efficiency of such lamps for producing light is one-third that of the open carbon arc lamps. This great loss in the efficiency of production of light is due to greater arc voltage (wasted in

the non-luminous arc stream), the lower current (efficiency is less at small currents), and the use of alternating current instead of direct current (alternating current is half as effective as direct current with the neutral carbon arc).

A special direct-current circuit with mercury rectifiers is used as the source of power for the magnetite arc, because this arc is unsuitable for operation on alternating current. This is also essentially an outdoor lamp, because of the products containing iron oxides from the arc. The electrodes, composed of non-combustible oxides, give as long life as enclosed arc carbons and have as low a cost of trimming. The light is of much higher efficiency than the enclosed arc and has a high horizontal candlepower which is desirable for street lighting.

About the year 1910, the first long-life enclosed-flame lamp for street lighting was developed. These lamps would operate for 125 hours with a single carbon trim consisting of a $\frac{7}{8}$ by 12-inch upper solid flame carbon and a 6-inch lower carbon. As with the enclosed-arc lamp, carbon electrode economy is secured by using the upper stub for the succeeding lower trim carbon. A later model of flame lamp was built, using $\frac{7}{8}$ by 14-inch carbons. These carbons give more light, longer life, decreased corrosion of metal and glass globe, and remarkable reliability and freedom from outage.

Searchlight Construction. — In the searchlight, the principal object is to obtain a light source as small and as bright as possible at the focus of the parabolic mirror, in order that the spread or angular dispersion of the beam will be as small and intense as can be obtained. It has been found that with a pure carbon shell and a white-flame core, the area of the positive crater is very much smaller than can be secured from a plain carbon; and the light-emitting power per unit surface is increased over threefold. The combined effect on the beam intensity is to give nine times as much light with less angular dispersion.

The evolution of the searchlight lamp has changed its weight from 9000 pounds to 300 pounds for the new type.

The diameter of the positive carbon for the 150-ampere white-flame high-intensity lamp is only 0.63 inch as compared with the older type searchlight with neutral-cored positive carbon having a diameter of 0.29–1.50 inches.

The high-intensity effect resides in a deep cup-shaped crater formed at the end of the positive flame carbon. The current goes to the bottom of the cup because the anode voltage to the flame core is only half that of the pure carbon shell. The great density of energy of several kilowatts (150 amperes at 40 volts) concentrated in about one cubic centimeter of white-flame vapor issuing from the core is the reason for high light emission.

Arcs for Motion-picture Projection. — Three classes of carbons are used for motion-picture projection work — solid, neutral-cored and white-flame.

Solid carbons have been used on low amperages both as positive carbons and as negatives. The neutral-cored positive is at present most widely used for motion-picture projection.

The use of metal-coated negatives for direct-current motion-picture projection is an American invention, and is important because of the improvement in the steadiness and amount of screen light. Arc steadiness is improved by the use of this negative, because it is much smaller in diameter than the unplated negative formerly used. The negative crater is confined to a smaller area. The arc voltage is reduced by about 5 per cent. The steadier arc and the decreased shadow of the smaller negative increase the screen illumination about 15 per cent for equal line power.

A further increase in candlepower of 50 per cent can be secured by lamps burning the positive carbon in a horizontal position and about at right angles to the negative. In this arrangement, the large positive crater is fully exposed and squarely faces the light-collecting condenser. Such right-angled operation is best accomplished with white-flame carbons.

For alternating current, there are two kinds of carbon trims in use: (1) neutral-cored carbons, and (2) white-flame cored carbons. Some of the advantages which result from the use of the latter as compared to neutral-cored carbons are (1) quiet, steady arcs with (2) whiter light, and (3) higher screen candlepower. The pictures appear clearer and with more perspective.

On direct current, the white-flame arc was slower in development but at present is making greater strides. The white-flame high-intensity positive at 75 amperes gives about three times as much screen light as the neutral-cored positive of the size commonly used. The gain in efficiency with this light comes from the higher crater brightness resulting from the luminescent vapors in the positive cup and the right-angle position of the positive carbon. The crater squarely faces the condenser and is exactly placed at the best optical position. The operation of these lamps is entirely automatic.

Electric Incandescent Lamps

[I. H. Van Horn]

Manufacture. — The industry of electric lighting may be said to have been born with the announcement in 1879 of the success of a trial installation set up by Edison at his laboratory in Menlo Park, N. J.

Edison offered a lamp to meet a condition which he considered essential to the success of electric lighting, namely, that the lamps operate in multiple so that the lighting or the extinguishing of one lamp need not affect the operation of any other.

The lamp developed by Edison consisted of a filament of high-resistance carbon hermetically sealed in a glass bulb from which all air had been removed. The development of this lamp was very rapid. The modern carbon filament lamp, except for the raw materials and the processes used in the preparation of the filament, is essentially the same as the lamps installed in the Pearl Street Station of the New York Edison Company in 1883. The older lamp had for its filament a carbon hairpin made from a strip of bamboo shaved down with a knife to a suitable size and carbonized after being bent to its final shape. The vacuum of the early lamps was slightly inferior to that obtained in the modern lamps. The filament of the modern 110-volt treated-carbon lamp is the carbon skeleton of a cellulose thread covered with graphitic carbon deposited upon it from decomposed gasoline. The 200-volt untreated-carbon filament lamps of to-day contain only the carbon skeleton of cellulose. The gem lamp contains a filament of the same materials as the 110-volt treated-carbon lamp, prepared in the same way but subjected to the intense heat of an electric furnace, both before and after the graphite coating has been applied. The electric furnace treatment converts the filament, and especially the coating, into a different form of graphite which will withstand higher temperatures than regular graphite and which is similar to a metal in its temperature coefficient of electrical resistance.

The gem lamp was followed by the metal filament lamps: first, the tantalum drawn-wire, next the pressed-filament tungsten, and finally the drawn-wire tungsten filament lamp which has generally superseded the other types, due to its superiority in efficiency and general operating characteristics.

The description of lamp manufacture which follows refers especially to the drawn-wire tungsten filament lamp. These lamps are divided into two general classes, vacuum and gas-filled. In the gas-filled lamps, the filament is usually coiled to reduce the energy loss from the filament due to gas conduction and convection. Fig. 25 is a sketch of a typical vacuum and a typical gas-filled lamp, giving the names of the lamp parts.

The lamp production of the United States amounts to more than 250,000,000 lamps per year. A result of large-scale production has been to establish special factories for producing lamp parts from the available raw materials. For example, glass works produce the glass parts, wire

works produce the filament and support wire, weld works produce the lamp leads, and base works produce the bases. The lamp parts are then taken to the lamp factory, where they are worked up into finished lamps. It is not within the scope of this work to give more than a brief sketch of the various steps in lamp manufacture.

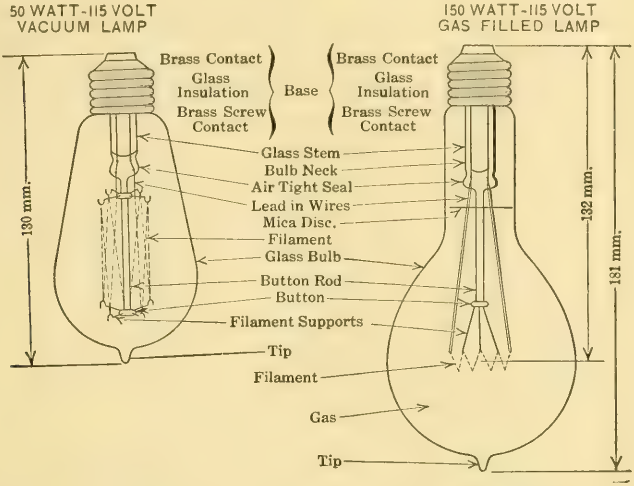


FIG. 25. Arrangement of Parts in Vacuum and Gas-filled Lamps.

Glass. — Glass is fundamental to the success of the incandescent electric lamp. In many respects it is an ideal material, for it is transparent; it can be readily worked into almost any shape; it is impervious to gases; it has high electrical and thermal resistivities; and it is rugged enough to withstand ordinary shocks. In the early days of lamp making the bulbs were blown without the aid of molds and accordingly individual bulbs varied greatly in their dimensions. Bulbs are now blown in molds and the sizes and shapes are within the control of the designer. The advent of the molded bulb made possible the elimination of much of the hand glass work formerly required in manipulating the glass in the subsequent operations of lamp making. The methods of drawing glass tubing were about the same up to a year or so ago as they have been for centuries, but tubing is now drawn automatically. The tubings and rods are carefully gauged and sorted into groups of sizes and then cut in lengths suitable for handling and shipping.

Tungsten Wire. — Since the advent of ductile tungsten wire, its use as a filament material has become almost universal. Tungsten metal was first isolated in 1783 but the method of working it was not discovered until the present century. Tungstic acid of high purity in the

form of a yellow powder is reduced to metallic tungsten by heating to red heat in hydrogen gas. The reduced tungsten is in the form of a powder with a dark gray appearance. The powder is then formed into slugs about $\frac{1}{4}$ to $\frac{1}{2}$ inch square and 16 inches long, by placing it in separable molds and compressing it under high pressure so that the grains cohere. This slug is then placed in a hydrogen furnace at a bright-red temperature to produce a slight surface fusion. After this treatment the slug may be handled without danger of breaking and it is then placed in an enclosed bottle through which hydrogen is flowing, and is gradually heated to a high temperature by passing a constantly increasing electric current through it. The resulting slug is hard, dense, bright, gray tungsten, which is ductile.

The treated slug is crystalline and the subsequent operations develop the groups of crystals into bundles of fibers by the hammering action of swaging machines and the stretching effect of dies. A tough fibrous structure results. Diamond dies are used in drawing the tungsten wire through its final stages. The diamond dies through which the tungsten wire is drawn are set in iron so that they may be operated at red heat. Tungsten wire is hard and the dies wear rapidly, so that they require frequent polishing.

Tungsten wire must be drawn in long lengths and to accurate sizes. Tungsten wire as small as 0.0005 inch in diameter has been produced. A quick method of accurately rating this wire is required, and a simple method for determining the diameter is to weigh a definite length of the wire. A torsion balance built on the principle of the Siemens electro-dynamometer, measuring torque in milligrams, has proved entirely adequate for rapid work.

Tungsten wire in proper sizes is supplied to the lamp factory ready for use for filaments and for filament supports.

Lamp Leads. — The wires used for leading the current from the lamp base through the bulb to the filament are termed leading-in wires, or leads. These wires must make an air-tight seal with the glass and must remain tight under the changes in temperature and pressure which are met with during the life of the lamp. In early days, platinum was the only metal which filled these requirements. Platinum has never been very plentiful and the many fields for its use have resulted in making it a very costly metal. Just enough of it was used in a lamp to make the seal with glass. The inner and outer leads were welded to the small platinum wires. The engineers in the lamp industry early saw the necessity for a cheaper wire for making this air-tight seal, and as a result a number of substitute wires were developed which worked equally as well as platinum. The wire in general use for this purpose is a composi-

tion wire made with a core of nickel-iron surrounded by a copper sleeve.

Automatic machines have been developed which electrically weld the inner and outer leads to the seal lead. The weld works prepares leads of the sizes required for lamp use and supplies them to the lamp factory ready for use in lamps.

Bases. — The lamp base is another very essential part of the lamp. Its function is to supply not only a mechanical means for supporting the lamp but also an electrical connection between the electrical supply line and the lamp leads. The brass parts are punched out of sheet brass, shaped and pressed into glass which electrically insulates and holds them in position. The bases are all pressed in dies of proper dimensions in order that they may fit standard sockets. The bases as shipped to the lamp factory are ready to be put on the lamps.

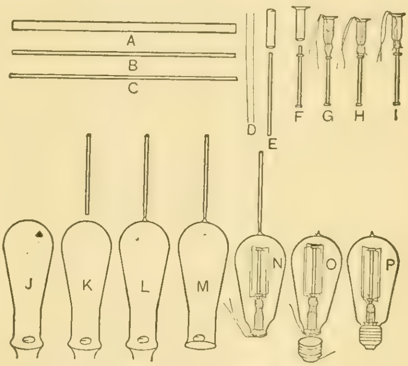


Fig. 26. Photograph of the Parts of a Tipped Construction Lamp Showing Some of the Stages in Its Assembly.

A shows stem tubing, B exhaust tubing, C cane glass for the arbor, D lead wires, E stem tubing, and cane glass cut to proper length, F the stem tube with a flange rolled on it and the cane glass with buttons formed, G the completed stem, H the stem with supports inserted in the buttons, I the completed mount with filament wire draped in place and attached to the lead wires; J a bulb as received from glass works, K a bulb with a hole blown in and an exhaust tube ready to be attached, L the tubulated bulb, M the tubulated bulb cracked off at the bead ready for sealing in. N shows the mount sealed into the bulb ready for exhausting, O an exhausted lamp with base ready to be attached, and P the based lamp ready for the customer.

Assembling the Lamp Parts. — The work of assembling the parts of a lamp (Fig. 26) is done in the lamp factory. One of the most essential elements in the preparation and assembling of lamp parts is cleanliness. The bulbs as received by the lamp factory are first washed internally with chemicals and then with water and allowed to dry. The bulbs are then ready to be tubulated. A hole is blown through the bulb and the small tube, which later serves as the exhaust tube for the lamp, is attached. The bulb is then cracked off at the bead, which is an enlarged portion of the neck left on when the bulb is blown, and is ready for the process of sealing in the mount. On machine-blown

bulbs, the bead is omitted, the bulbs being received at the factory ready for direct sealing to the mount.

Tubing as received in the lamp factory is in lengths of about 4 feet. At the factory it is cut into lengths suitable either for tubulating bulbs, or for stem flanges. The tubing which has been cut to the proper length for flanges is then placed in an automatic machine and flanges are rolled. The cane glass (glass rod) in 4-foot lengths is put into the button-making machine which automatically feeds the cane glass into the machine, forming buttons of the desired size on the cane. The next operation consists in assembling the leads, the flanges and the button rods into one part known as the stem. This work is done on a semi-automatic machine known as the stem machine. When the stem is completed, supports are inserted into the button and hooks formed. This work is done on the support-inserting machine.

The tungsten filament wire is wound on special forms which shape or mark the wire into sections of known lengths. For the gas-filled lamps, the filament wire is coiled into helical coils on mandrels (wire in this case) on special coiling machines or lathes adapted for this work. The mandrel wire is removed chemically from the small coils and mechanically from the large coils. The formed filament wire is draped over the small wire supports and attached to the inner leads, completing the mount which is then ready to be sealed into the bulb. In the case of the vacuum lamp, a chemical called a " getter " is usually placed on the mount before it is sealed into the bulb.

The sealing operation is performed on a semi-automatic machine which holds the mount in an upright position in the bulb, while the seal is being made. The bulb is melted down so that it makes an air-tight joint with the flange.

The lamp is then taken to the exhaust machine where the air is pumped out of it by means of vacuum pumps. The lamp is ordinarily placed in an oven during this process, in order to assist in removing moisture and other volatile matter from the inner parts of the lamp. The lamps to be exhausted are fed into one side of the machine and at the completion of their travel through the oven are tipped off. The gas-filled lamp is filled with the proper gas at a known pressure before it is tipped off.

From the exhaust machine, the lamps are passed to the flash-aging machine where the filament is first heated up to its operating temperature. In the case of the vacuum lamp, as has been stated, a certain chemical or " getter " has been placed in the lamp which assists in " cleaning up " (making inactive) the residual gases in the lamp at the time the filament is lighted on the flash-aging machine. This clean-up

of gases is usually accompanied by a blue glow known as the Edison effect, and its disappearance is an indication that the residual gases have been cleaned up and that the vacuum has been perfected.

The next step in the completion of the lamp is attaching the base to the lamp. The base is coated with cement, placed in position on the lamp, and passed through an oven in order to drive off the volatile matter from the cement and to set it. The outer lead wires are then soldered, one to the center contact and the other to the shell contact.

The lamp is then cleaned, lighted for inspection, labeled so as to designate the wattage and voltage or current, packed and shipped to the customer ready for service.

The quality and value of the finished lamp depends on the care and skill used in preparing the lamp materials and in assembling them into the finished lamp. Many of the processes must be controlled within very close limits. The services of a large number of scientific men have been utilized in studying the problems of lamp manufacture and production.

Properties of Tungsten

Temperature Scale. — A relation showing how the temperature varies with some arbitrarily chosen property of a material, e.g., resistivity, total emission per unit of area, brightness, constitutes a temperature scale of the material. For filaments used as light sources, a scale relating temperatures in ° K. to brightness in $\frac{\text{candles}}{\text{cm.}^2}$ is most appropriate. For tungsten such a calibration has been carried out on a tubular filament with small holes penetrating its walls. The radiations from the small holes were almost completely black and permitted the application of black-body laws in measuring temperatures corresponding to brightness, which were determined by ordinary photometric means. Variations in various properties of tungsten which depend on this scale are shown in Table XIX. The data in this table show among other things that (1) relatively the brightness increases much more rapidly than the temperature, i.e., $\frac{dB_n}{B_n} \Big/ \frac{dT}{T}$ is much greater than unity; (2) that this ratio, $\frac{dB_n}{B_n} \Big/ \frac{dT}{T}$, decreases with temperature; thus at 2000° K a 1 per cent change in T is accompanied by 12.3 per cent change in B_n, while at 3000° K the change is 8.3 per cent; (3) that the total emission, E, varies similarly though less pronouncedly; and (4) that the luminous efficiency varies similarly and more pronouncedly. At 2450° K, the

approximate operating temperature of the 50-watt vacuum tungsten lamp, the values for B_n, E and ϵ are respectively about 190 $\frac{\text{candles}}{\text{cm.}^2}$, 64 $\frac{\text{watts}}{\text{cm.}^2}$, and 10 $\frac{\text{lumens}}{\text{watt}}$.

TABLE XIX

Data on Tungsten

Applicable to wires at constant temperature throughout their lengths, mounted *in vacuo*

T ° K.	T_c	B_n $\frac{\text{Candles}}{\text{cm.}^2}$	$\frac{T\,dB_n}{B_n\,dT}$	E $\frac{\text{watts}}{\text{cm.}^2}$	$\frac{T\,dE}{E\,dT}$	ρ ohm-cm.	$\frac{T\,d\rho}{\rho\,dT}$	ϵ $\frac{\text{lumens}}{\text{watt}}$	$\frac{T\,d\epsilon}{\epsilon\,dT}$	$\frac{l}{l_0}$	$\frac{L}{L_{2450}}$	$\frac{T\,dL}{L\,dT}$
2000	2038	20.0	12.28	24.2	4.86	.04592	1.200	2.77	7.42	1.0088	......	−51.5
2100	2143	35.9	11.74	30.6	4.81	.04628	1.200	3.95	6.93	1.0094	......	−48.9
2200	2248	61.4	11.22	38.3	4.75	.04664	1.200	5.40	6.47	1.0101	115.	−46.5
2300	2355	99.8	10.77	47.2	4.70	.04700	1.200	7.15	6.07	1.0108	15.1	−44.4
2400	2464	156	10.33	57.7	4.65	.04737	1.200	9.15	5.68	1.0116	2.40	−42.3
2500	2575	234	9.93	69.7	4.60	.04774	1.200	11.4	5.33	1.0124	.427	−40.5
2600	2685	344	9.56	83.3	4.56	.04811	1.200	14.0	5.00	1.0132	.0891	−38.8
2700	2795	492	9.21	98.9	4.52	.04849	1.200	16.9	4.69	1.0140	.0209	−37.2
2800	2908	688	8.88	116.6	4.48	.04887	1.200	20.0	4.40	1.015	.00589	−35.8
2900	3021	939	8.58	136	4.44	.04925	1.200	23.4	4.14	1.016	.00182	−34.4
3000	3137	1255	8.30	158	4.40	.04964	1.200	27.1	3.90	1.017	.000575	−33.2

T refers to the true temperature in ° Kelvin (° Centigrade + 273°).

T_c refers to the color temperature in ° Kelvin (° Centigrade + 273°).

B_n refers to normal brightness. The average brightness taking account of all directions is about 5 per cent greater.

E refers to radiation intensity. Strictly speaking, owing to disregard of thermal expansion, the unit is a watt per cm.² of surface as measured at room temperature.

ρ refers to resistivity. Strictly speaking, owing to disregard of thermal expansion, the unit is an ohm-cm. with the measurement of length taken at room temperature.

ϵ refers to luminous efficiency. Account has been taken of thermal expansion and of variation between normal brightness and average brightness.

l/l_0 refers to the length at temperature T divided by the length at room temperature.

L/L_{2450} refers to life at temperature T divided by life at 2450° K.

Color Temperature. — The experimental basis for the concept of color temperature is the fact that the radiations of most incandescent sources match in color quite closely with those from a black body at suitably chosen temperatures. Generally, if not always, the same integral color for incandescent sources means the same relative distribution of radiation in the visible spectrum. Accordingly, the color temperature of a source is defined as the temperature of a black body which has the same spectral distribution of radiation through the visible spectrum as the source in question. The matching may be performed integrally with an ordinary photometer, or wave-length by wave-length with a spectrophotometer.

The color temperature of tungsten at 2450° K. is quite closely 2500° K. That tungsten at 2450° K. has the same relative spectral distribution throughout the visible as a black body has at 2500° K. is qualitatively shown in Fig. 6. That the relative distribution is actually the same is evident when the ordinate units for the two curves are arbitrarily so chosen that they coincide at some wave-length in the visible. This has been done in Fig. 27 in which the spectral energy curves of tungsten, untreated carbon, and a black body at a color temperature of 2200° K. are shown.

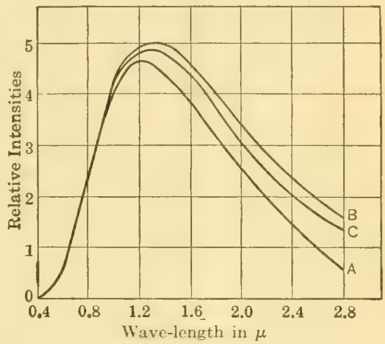


FIG. 27. Spectral Energy Curves for Tungsten (A), Black Body (B) and Untreated Carbon (C) at a Color Temperature of Approximately 2200° K.

Certain substances have spectral luminosity curves which differ so greatly from black-body curves that color temperatures cannot be assigned to them.

Radiating Properties. — As shown in Fig. 6, the spectral energy curve of tungsten at 2450° K., the approximate normal operating temperature in the vacuum lamp, is much like that for a black body at the same temperature. Certain differences are evident, however:

(1) The wave-length of maximum emission intensity, λ_m, for tungsten is slightly less than for a black body. It is at 1.15μ instead of 1.18μ;

(2) The spectral emissivities of tungsten progressively decrease in proceeding to longer and longer wave-lengths. Thus at 0.6μ, 1.0μ, 2.0μ and 4.0μ, they are 0.44, 0.33, 0.26 and 0.19, respectively. This progressive change is the cause of the difference in λ_m just previously noted and shows also that tungsten filaments belong to that class of non-black bodies which radiate selectively. For light production, this selectivity is distinctly favorable.

Variations in the radiating properties with temperature are shown by the emissivity curves of Fig. 28. The total emissivity curve shows a marked variation with temperature; starting at about 10 per cent at 1000° K., it increases to about $31\frac{1}{2}$ per cent at the ordinary vacuum-lamp temperature of 2450° K. and to about 38 per cent at the melting point, 3655° K. This change is in considerable part explained by the shift in the center of the spectral energy curve from the far infra-red where the spectral emissivity of tungsten is relatively low to the near visible where the spectral emissivity is relatively large. The average

visible emissivity, on the other hand, shows a slight decrease with increase in temperature, changing from about 50 per cent at 1000° K. to about 42 per cent at the melting point. This gradual approach of the two emissivities as the temperature is increased indicates that the favorable selectivity of tungsten becomes relatively less important as the temperature increases. At temperatures above 4500° K., the temperature at which the two emissivity curves are assumed to cross, the selectivity of tungsten would be a disadvantage in light production.

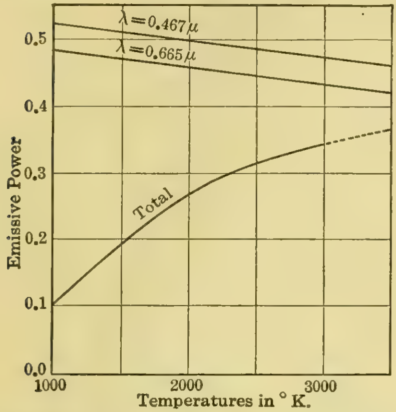


Fig. 28. Spectral and Total Emissive Powers of Tungsten.

The above analysis by spectral energy curves and emissivities gives a complete statement of the selectivity of the radiation. A briefer but still important statement of the selectivity from a light-production standpoint is contained in the color temperature — true temperature relation. Where the color temperature differs from true temperature, there is necessarily selectivity of radiation. If the color temperature is the greater, as in tungsten, the emissivities for the shorter visible wave-lengths are greater than for the longer wave-lengths. If this decrease in emissivity with increase in wave-length persists into the infra-red, as in tungsten, the body possesses a favorable radiating selectivity. If the tendency is the opposite, the selectivity is unfavorable. Other things being the same, the greater the difference between the color and the true temperatures, the greater the favorableness or unfavorableness. Unfortunately, the color temperature — true temperature data are at present quite meager for substances other than tungsten and do not permit illustrations of this point. Values for tungsten are included in Table II.

Resistance to Vaporization. — Data on the vaporization of tungsten (Table XX) were obtained by measuring the loss in weight of various filaments which were operated at various temperatures *in vacuo* for different lengths of time. These losses in weight, combined with the initial dimensions of the filaments, the density of tungsten, and the time of operation, yield directly, for the temperature concerned, the rate of vaporization, a quantity expressible in grams per square centimeter.

That vaporization is the principal factor in the life of tungsten lamps

has been thoroughly demonstrated. Table XX includes among other things the rate of vaporization of the lamp filament at normal temperature and at the temperature used by certain manufacturers in testing their product, and the lives of these lamps as determined by experience. The relative decrease in life resulting from the increased temperature is quite closely the same as the relative increase in the rate of vaporization. The very close agreement is taken as evidence of the predominating importance of the vaporization factor.

TABLE XX

Data Showing Relation Between the Rate of Vaporization of Tungsten and the Life of a 60-Watt Tungsten Lamp

Condition	Efficiency Average	True Temperature (Average)	Life	Rate of Vaporization
Normal.....	$10.0\frac{\text{lumens}}{\text{watt}}$	2437° K.	Over 1000 hours	$7.25\times10^{-10}\frac{\text{grams}}{\text{cm.}^2\text{ sec.}}$
Test........	13.3 "	2563° K.	130 hrs. to 140 hrs.	5.50×10^{-9} "
Ratio.......	....	....	7.4	7.6

Superiority as a Filament Material. — In fixing upon a suitable material for a lamp filament, there are several questions to be considered. Of those involving physical properties, everything simmers down chiefly to their contributions toward the amount of light that may be obtained when constructed in convenient-sized units for a given input of energy and, to some extent, to the spectral character of the light emitted. In comparing different materials consideration must not only be given to the radiating selectivities at any given temperature, but also to the practical temperatures of operation.

At present, because the temperature scales for other materials than tungsten are not known, it is not possible to compare selectivities at a given true temperature. However, in consequence of the ease of making color matches, it is possible to make a comparison of radiating properties, showing selectivities under the conditions of the same color temperature. Table XXI thus shows the lamp efficiencies for various incandescent sources at color temperatures 1700° K. and 2160° K. A difference in efficiency at color match is positive evidence of selectivity of radiation, since evidently the differences can only be due to a failure of the spectral energy curves as plotted in Fig. 27 to coincide in the infra-red. Lacking data on comparisons at the same true temperatures, one may take, for purposes of comparison, as a measure of selectivity

the ratio $\frac{\epsilon - \epsilon_0}{\epsilon_0}$, where ϵ_0 and ϵ represent respectively the efficiencies of the black-body and of the source in question at the same color temperature. This method of expressing selectivity is of considerable value in that one can tell at a glance how different sources range themselves as to favorableness in light production.

Table XXI shows an increasing selectivity from the black body to osmium. It is to be noted that the positions of the black body, untreated carbon, and tungsten are consistent with the results plotted in Fig. 27, and that while tungsten is very favorably selective, osmium is more so. The fact that tungsten is used commercially to the exclusion of osmium rests upon other properties.

TABLE XXI

Data Showing Radiation Selectivities of Various Sources at Two Color Temperatures

Source	T_C = 1700° K. (approx.)		T_C = 2160° K. (approx.)	
	Efficiency in $\frac{\text{Lumens}}{\text{Watt}}$	Selectivity in Per Cent	Efficiency in $\frac{\text{Lumens}}{\text{Watt}}$	Selectivity in Per Cent
Black body (computed)	0.33	00	2.8	00
Untreated carbon	0.39	18	3.5	25
Flashed carbon	0.41	24	3.7	32
Graphitized carbon (gem)	0.41	24	3.7	32
Tantalum	0.50	51	3.9	39
Tungsten	0.59	78	4.4	57
Osmium	0.72	118	4.9	75

The great determining factor in favor of tungsten as a filament material is its low rate of vaporization, a fact probably connected with its very high melting-point temperature, 3655° K. This means that for the same length of life tungsten may be operated at a much higher color temperature, as well as true temperature, than is possible with osmium, for instance. The increased luminous efficiency that comes with this increase in temperature much more than offsets the more favorable selectivity of osmium. To illustrate, compare tungsten and graphitized carbon, a material which was used extensively in the gem lamp. Table XXI shows that at 2160° K., the approximate operating color temperature of the gem lamp, tungsten has the advantage in selectivity of $\frac{(1 + 0.57) - (1 + 0.32)}{(1 + 0.32)}$ or about 20 per cent. With each

at its normal operating temperature, the selectivity factor is reduced to about 15 per cent. However, under those conditions — the life of the carbon filament is then only half that of the tungsten filament — their efficiencies are respectively about $4.2\ \frac{\text{lumens}}{\text{watt}}$ and $10\ \frac{\text{lumens}}{\text{watt}}$, or about 140 per cent excess in favor of tungsten. Of this 15 per cent is ascribable to selectivity and the remaining 125 per cent to its lower vaporization rate.

This same temperature factor, in case it shall ever be found practicable to make carbon filaments which can operate for the same life at a sensibly higher temperature than is possible for tungsten, may in a similar way overcome the more favorable selectivity of tungsten and lead to the adoption of carbon as a filament material for vacuum incandescent lamps.

Testing

The main purpose of testing lamps is to determine their life-performance characteristics. Under life performance of lamps, some of the factors that should be considered are initial rating, lumen maintenance, burn-out life and mechanical hardness.

The initial photometric rating of the lamps gives the amperes, lumens and lumens per watt at labeled volts, and tells whether the lamps come within the allowable limits for these quantities. After the lamps have been rated, they are usually put on test at either labeled volts or at the volts for some definite lumens per watt. The lamps are measured at various intervals during life to determine how well they maintain their lumen and current values. The ideal lamp from the standpoint of performance is one that remains in service for its rated hours of life and maintains its lumen and current values constant. This ideal is seldom realized in practice and the tests serve to measure the departure from this ideal.

It is not essential to have an elaborate equipment for conducting lamp tests, but what is used must fulfil certain fundamental requirements. The photometer, the test racks, the electrical supply and the control apparatus should be reliable and of known accuracy, so that the proper use may be made of the test results.

Photometers. — Lamps are rated both initially and during life on photometers, and unless the measurements are carried out with reasonable care, the results are likely to be misleading. At the present time the sphere has almost entirely superseded the ordinary bar photometer for incandescent lamp testing. The spheres in use vary in size from about 30 inches in diameter for miniature lamps to 100 inches for large

lamps and extended life testing. In general, the contrast type of photometer head is employed with the sphere, and together with the comparison lamp is mounted in an enclosed box. The photometric setting is made by changing the distance of the comparison lamp. The standards are rated in lumens and preferably should be of the same type as the lamps to be measured. In life testing, in particular, they should be checked frequently. Absorption strips and colored glasses are employed to overcome the color difficulties and extend the range of the instrument. The sector disk is also used for the latter purpose. The employment of skilled operators, who are thoroughly familiar with the use and maintenance of the apparatus, is essential for reliable results.

Test Racks. — A test rack should be so constructed that the voltage at the socket can be controlled. To accomplish this two methods are in common use: either a small transformer for each individual circuit containing from one to ten lamps, or a large transformer with taps for the different voltages required. Additional range is sometimes obtained by inserting resistance in series with each socket. Spacing is determined by considerations of convenience, and the necessity of keeping down temperature. It is desirable to keep the voltage drop in the sockets and lines down to a low value so that the voltage at individual sockets may be fairly constant even under different loadings of the rack. The test rack should provide some flexibility as regards the position of lamps. Those that are meant for tip-up burning should be tested tip-up; those that are to be used in enclosed units should be tested in enclosed units.

Electrical Supply. — Owing to the quite general adoption of alternating current for commercial service, it is common to use alternating current for life testing. For ideal testing conditions, the voltage at the test socket should be maintained constant throughout the test. The limits within which the voltage can be maintained depend upon the equipment provided. As practically no commercial supply is constant over an extended period, it is generally desirable to provide a separate source whose regulation can be controlled by the operator. If a large number of lamps are to be tested, the problem of electrical distribution is important. For convenience in testing, the voltage drop between the center of distribution and the test sockets should be small, to avoid the necessity of large corrections. The maximum variation of voltage at the test socket may be easily kept within a volt for a well-designed and well-maintained equipment.

Control Apparatus. — A very essential piece of equipment for accurate life testing is a high-grade time-clock, which will enable the computation of the total number of hours that the life-test racks operate during any

period. The time at which lamps are put on or taken off is stamped in the usual manner. By the use of suitable electrical equipment the clock can be made to run only when the racks are in operation.

Accurate electric meters should be provided for checking the constancy of the electrical supply. Provision must be made to prevent over- and under-voltage on the test lamps. This may be accomplished by the use of suitable over- and under-voltage relays.

Methods of Testing. — The number of lamps required to give representative test results obviously depends on the uniformity of the individual lamps. Anyone with experience in lamp testing knows that lamps may vary considerably in their individual performance, and for this reason it is customary to life-test at least five lamps from any single group. Some particularly large users of lamps buy them under specifications and make acceptance tests on a small percentage of the lamps purchased. However, the average customer makes no special test of lamps. His judgment of their quality is based on the service which they give. The lamp manufacturer finds it is desirable to make tests of his own product in such quantities that he may satisfy himself as to the merits of his output. It is sound business for him to deliver a product which fully lives up to the standard which he advertises.

It is desirable to test lamps under conditions approximating the service requirements for the type of lamp involved. Lamps designed for constant-voltage service should be tested on constant-voltage circuits; lamps for constant-current service should be tested on constant-current circuits; lamps for series burning should be tested in series.

One drawback to making life tests is that it takes a long time to complete the tests under normal conditions of burning. An analysis of a large number of life tests has shown that there is a fairly definite mathematical relationship between the lives of lamps operated at different efficiencies. Thus, if the life at one efficiency is known, it is possible to compute the probable life at some other efficiency after having once determined the mathematical constants involved. This so-called life-efficiency characteristic is commonly expressed by the equation

$$\frac{L_1}{L_2} = \left(\frac{E_2}{E_1}\right)^b$$

where L_1 and L_2 are the lives at E_1 and E_2 lumens per watt respectively and b has a value which is determined by a large number of actual tests at different efficiencies, and may range from 6.5 to 7.5 for the ordinary lamps.

By testing lamps at a high efficiency, it is possible to complete a life-test in a comparatively short time. This is referred to as "forced"

testing. Thus a lamp which would require 1000 hours' burning for test at normal efficiency can be tested in from 100 to 200 hours by raising the voltage approximately 15 per cent. The chief argument for forced tests is the saving of time; the argument against it is that the exponent, b, which has been determined, is an average value and may only be approximately correct for the particular test involved, and, as a result, the interpretation of the results may be in error. Normal efficiency tests are preferable and should always be used as a final criterion of lamp quality.

Records. — In any system of lamp testing, the lamps tested should be so marked that there is no possibility of a mistaken identity during the period covered by the test. Paper labels are not satisfactory for this purpose. Etching inks provide a very permanent marking. The records kept should furnish a complete history of each lamp during the test. The records should be permanent and readily accessible, so that at any future date they may be referred to in compiling lamp information.

Evaluation of Results. — Much of the value to be obtained from life-tests may be lost unless they are analyzed and evaluated. The value of a lamp for producing light is a function of total life, initial efficiency, and average efficiency during life. In general, the lamp which maintains the highest average efficiency for a given number of hours total life is the best lamp. It must be borne in mind, however, that lamps which may perform well in one service may prove wholly unsatisfactory in another, owing to the special conditions which may exist. Therefore, in any interpretation of results, it is very important to state the conditions and limitations of the test.

Characteristics of Incandescent Lamps

Characteristic Curves. — Increasing the voltage of a lamp results in higher filament temperature, a higher light output, a higher wattage input, and a shorter life. The light output increases at a higher rate than the wattage input and, therefore, a higher lumens per watt is obtained. The variation of amperes, watts, ohms, lumens (candle-power) and lumens per watt with varying volts can be determined experimentally on a photometer. Such values plotted on coördinate paper produce smooth curves which are referred to as the characteristics of incandescent lamps. Fig. 29 shows a typical set of these characteristic curves for a vacuum tungsten lamp.

The 100 per cent values on these curves are the values at 10 lumens per watt, which is usually taken as the normal operating efficiency of vacuum lamps used on multiple circuits. The operating characteristics

of gas-filled lamps vary slightly because of their different forms of filament construction, but for most practical purposes the above curves for the vacuum lamps may be used for the gas-filled.

It will be noted from these curves that a 10 per cent increase in volts corresponds to a 4 per cent increase in ohms, a 6 per cent increase in

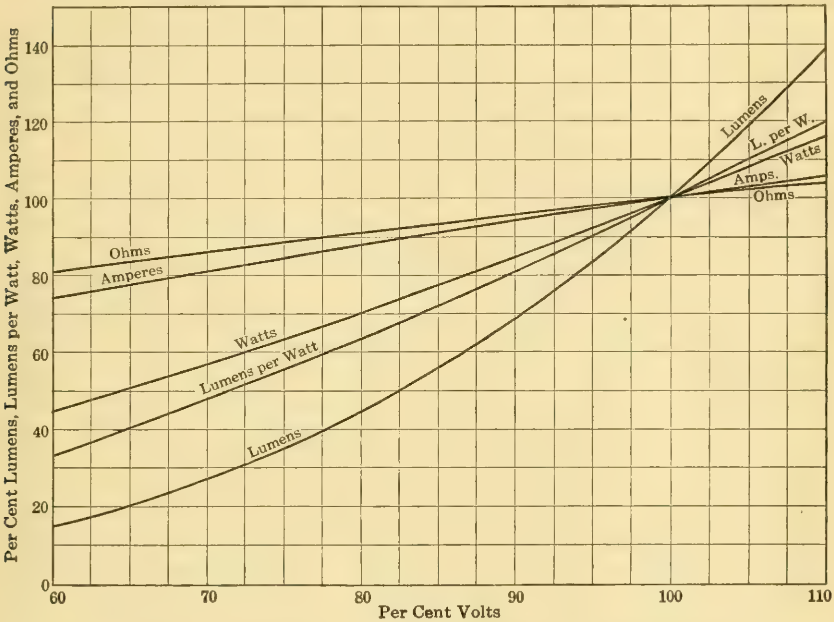


FIG. 29. Characteristic Curves for a Vacuum Tungsten Lamp.

amperes, a 16 per cent increase in watts, a 20 per cent increase in lumens per watt and a 39 per cent increase in lumens (candlepower). These curves are logarithmic functions and can be expressed in the form of exponential equations.

Characteristic Equations. — To determine these curves or equations, measurements of amperes and lumens at different voltages are made on a photometer. The relations between amperes and volts and between lumens and volts are, therefore, the fundamental characteristics from which the relations of ohms and volts, watts and volts, and lumens per watt and volts are derived. Equations expressing the relations of these various quantities for vacuum tungsten lamps have been worked out by several investigators, but those given in Scientific Paper No. 238 of the Bureau of Standards are generally accepted as the most satisfactory for use over wide ranges of voltage. The equations are as follows:

TABLE XXII

CHARACTERISTIC EQUATIONS

$$
\begin{aligned}
y_1 &= 0.918\,x^2 - 2.009\,x + 0.07918 \\
y_2 &= -0.946\,x^2 + 3.592\,x \\
y_3 &= -0.028\,x^2 + 1.583\,x \\
y_4 &= -0.028\,x^2 + 0.583\,x
\end{aligned}
$$

where x = log voltage ratio
y_1 = log actual watts per candle (w.p.c.)
y_2 = log candlepower ratio
y_3 = log wattage ratio
y_4 = log current ratio.

A set of tables taken from this Scientific Paper will be found at the end of the present chapter. If the fundamental quantities are known at one voltage, they may be found, by means of these tables, for any other voltage. In ordinary commercial practice the fundamental equations are usually expressed in the following form:

$$(1)\quad \frac{I_1}{I_2} = \left(\frac{v_1}{v_2}\right)^t \qquad\qquad (2)\quad \frac{L_1}{L_2} = \left(\frac{v_1}{v_2}\right)^k$$

in which I_1, L_1 and v_1 are values of amperes, lumens and volts respectively at some reference efficiency, and I_2, L_2 and v_2 are the corresponding values at some other efficiency. The exponents, t and k, are constants whose values depend upon the fundamental efficiency chosen and the type of lamp involved, and the equations are correct only for small changes in voltage. For regular tungsten vacuum lamps, the values of t and k are approximately 0.58 and 3.51 respectively, when referred to a fundamental efficiency of 10 lumens per watt. Having once determined the values of these exponents, it is possible to compute from equations (1) and (2) the values of amperes and lumens for any voltage within 5 volts (or 10 if too great accuracy is not needed), provided the amperes and lumens at some one voltage are known. For instance, if a certain lamp, operated at 115 volts, takes 0.43 ampere and gives 480 lumens, what would be the values of amperes and lumens if the lamp were operated at 110 volts? Substituting the known values in equations (1) and (2)

$$(1)\quad \frac{0.43}{I_2} = \left(\frac{115}{110}\right)^{0.58}$$

$$(2)\quad \frac{480}{L_2} = \left(\frac{115}{110}\right)^{3.51}$$

and solving these equations for I_2 and L_2 it is found that

$$I_2 = \frac{0.43}{\left(\frac{115}{110}\right)^{0.58}} = 0.41 \text{ ampere,} \quad \text{and} \quad L_2 = \frac{480}{\left(\frac{115}{110}\right)^{3.51}} = 412 \text{ lumens.}$$

The efficiency-voltage characteristic derived from the fundamental relations of equations (1) and (2) is very commonly used and is given in the equation

$$(3) \quad \frac{E_1}{E_2} = \left(\frac{v_1}{v_2}\right)^g$$

where E_1 and E_2 are the lumens per watt values obtained at voltages v_1 and v_2 respectively and g is an exponent which may be derived from the values of the t and k exponents of equations (1) and (2).

Resistance Curves. — In comparing the characteristic curves of tungsten filament lamps with those of carbon lamps, a considerable difference is noted. The differences in electrical-resistance characteristics are most marked. Fig. 30 shows typical resistance curves for untreated carbon, treated carbon, metallized carbon (gem) and tungsten lamps. The untreated and treated curves show decidedly negative temperature coefficients of resistance, whereas the metallized carbon and the tungsten curves show decidedly positive temperature coefficients. The ratio of hot to cold resistance is approximately 0.55 for untreated carbon, 0.50 for treated carbon, 1.43 for metallized carbon and 13.0 for tungsten. The effect of these differences is very noticeable in the operation of the different lamps. With untreated and treated carbon lamps, the initial current when full voltage is applied is less than normal, whereas with the tungsten filament lamp it is many times the normal value. It is commonly known that a tungsten lamp comes up to full brilliancy much quicker than the carbon lamp of equal wattage. The reason for this is that the initial rate of energy input is greater for the tungsten lamp. The overshooting of current in tungsten lamps is ordinarily of such short duration that the fuses in the circuit do not fail even though their continuous rating is greatly exceeded.

Overshooting in Candlepower. — The impression has prevailed among a good many people that the tungsten lamp overshoots in candlepower. Accurate observations indicate that there is no such overshooting in the ordinary vacuum lamp and that the apparent momentary increase in the filament brightness is an optical illusion. A consideration of the instantaneous values of current and voltage show that it is not possible in this lamp to heat the filament above its normal temperature. As the filament comes up to temperature, the

filament resistance increases and cuts down the current so that when the filament reaches its normal temperature the wattage input is also normal.

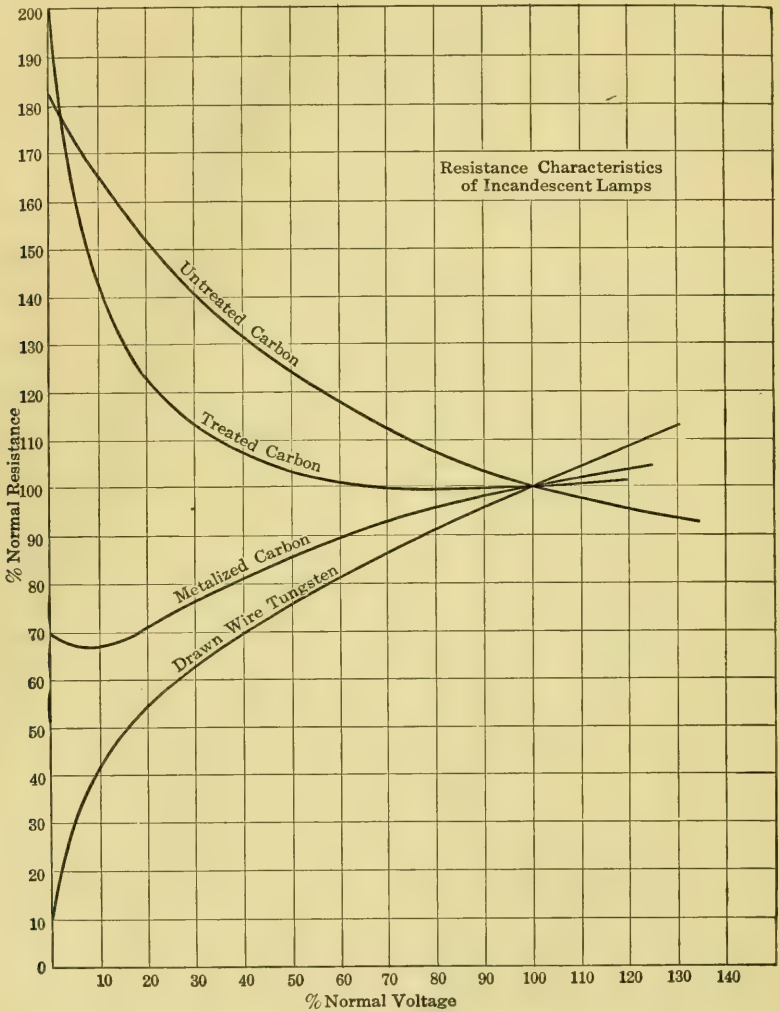


FIG. 30. Resistance Characteristics of Incandescent Lamps.

There are some special conditions which make it possible to get an overshooting in candlepower. For instance, a lamp which operates normally with a relatively high voltage drop in the leads in proportion to the voltage on the filament may produce such a condition because of the slowness with which the leads come up to their operating tempera-

ture. When the lamp is cold, the voltage drop in the leads is small on account of the relatively low resistance of the leads. On throwing the lamp in circuit, the filament heats up more rapidly than the leads and consequently a greater proportion of the voltage is impressed on the filament than is normal. In the gas-filled lamp, the gas within the bulb normally operates at a pressure considerably higher than the pressure at room temperature. The gas and the parts in the lamp heat up much more slowly than the filament; therefore, the filament has an opportunity to burn in a gas at much lower pressure than it does under the steady burning condition and may produce an overshooting in filament temperature. When the parts of a lamp are cold, more heat is conducted away from the filament at the points of support and may result in overheating the uncooled portions.

Effect of Line-voltage Fluctuations. — The tungsten lamp is less affected by poor line-voltage regulation than the carbon lamp, because a given change in voltage makes less change in the wattage input of the tungsten lamp. As has been mentioned previously, the tungsten filament resistance increases with increased applied voltage, whereas the resistance of the carbon filament is almost constant in the operating range. An increase of 10 per cent in volts would cause an increase of 16 per cent in watts for the tungsten lamp as compared with a 21 per cent increase in watts for the carbon lamp. At 50 per cent volts the tungsten lamp would take 33 per cent watts as compared with 24 per cent for the carbon lamp. Thus at low voltages the tungsten lamp gives appreciably more light than the carbon.

Flicker. — A large percentage of the incandescent lamps in use are burned on 60-cycle alternating-current circuits. There are localities, such as the Niagara Falls district, however, where 25-cycle current predominates. It is general experience that the lower-wattage tungsten lamps show flicker on 25-cycle circuits.

The filament of the 25-watt tungsten lamp is about 0.001 inch in diameter and its heat capacity is very small. Measurements of the instantaneous candlepower for the 25-watt lamp on 25-cycle current show a variation in candlepower of 30 per cent above and below the average. This variation is sufficient to cause visible flicker under ordinary conditions of illumination. Flicker is much more noticeable at low intensities. Carbon lamps show much less flicker than tungsten lamps of the same candlepower, because the filament is larger in the carbon lamp of corresponding candlepower. None of the ordinary lamps show visible flicker on 60-cycle current.

The rapid cooling and the quick heating of small tungsten filament lamps make them especially suited for flashing signs. During the

recent war, special lamps were designed for sending Morse code signals. The highest-speed lamp for this service was found to be a lamp with a very thin tungsten-ribbon filament operated in a hydrogen atmosphere. Hydrogen has the highest heat conductivity of any of the gases.

Reduction in Rate of Vaporization. — That the introduction of a chemically inert gas into an incandescent lamp reduces the rate of vaporization of the filament is easily shown. The operation of two tungsten lamps which are identical in construction except that one is a vacuum lamp and the other a gas-filled lamp at the same very high temperature gives convincing visual proof. A few minutes of operation at a rightly chosen temperature will cause considerable blackening of the bulb of the vacuum lamp without appreciable blackening of the other. It is as though the vaporization of the filament, which consists of the escaping of the filament material atom by atom, were hindered in the gas-filled lamp by the surrounding gas, in that the escaping atoms, before being well freed from the filament, or more precisely from the thin enclosing layer of saturated vapor of the filament material, were to a large extent driven back by the bombardment of the surrounding gaseous molecules. In consequence of this, the filament for a given rate of vaporization or life may be operated at a much higher temperature in the gas than *in vacuo.* This reduction in the rate for a given temperature for ordinary argon-filled lamps is of the order of 1:100. Thus, if the gas were removed from a gas-filled lamp and the filament still operated at the same high temperature, a life of about 10 hours instead of 1000 hours would be expected.

Gas Loss. — That a very appreciable gaseous conduction loss occurs in gas-filled lamps is also readily shown. The simplest test consists in touching cautiously with the finger the bulbs of lighted vacuum and gas-filled lamps of approximately the same wattage. The burning sensation likely to follow too long contact with the gas-filled lamp in contrast to that of moderate coolness for the vacuum lamp is first-hand evidence that energy is conveyed from the filament to the bulb in the gas-filled lamp by a method entirely absent or of little effect in the vacuum lamp.

A second test for gas loss, which is of a visual character, yields equally striking evidence. Two lamps, differing only in that one is gas-filled while the other is evacuated, lighted up by means of the same current, show a considerable difference in filament brightness, the filament *in vacuo* being the brighter. The reduced brightness of the gas-filled lamp is a result of the added method of disposing of the energy supplied. The contrast becomes more and more noticeable as the current through the lamps is reduced. If another similar pair of lamps with a very

different sized filament be similarly operated, it will also be evident visually that the smaller the filament, the greater is the gas loss measured in per cent of the total input of the lamps.

This dependence of gas loss on filament size is shown in Fig. 31. The plot shows, for instance, that a straight 5 mil (0.005 inch) tungsten filament at 2445° K., operated successively *in vacuo* and in nitrogen at

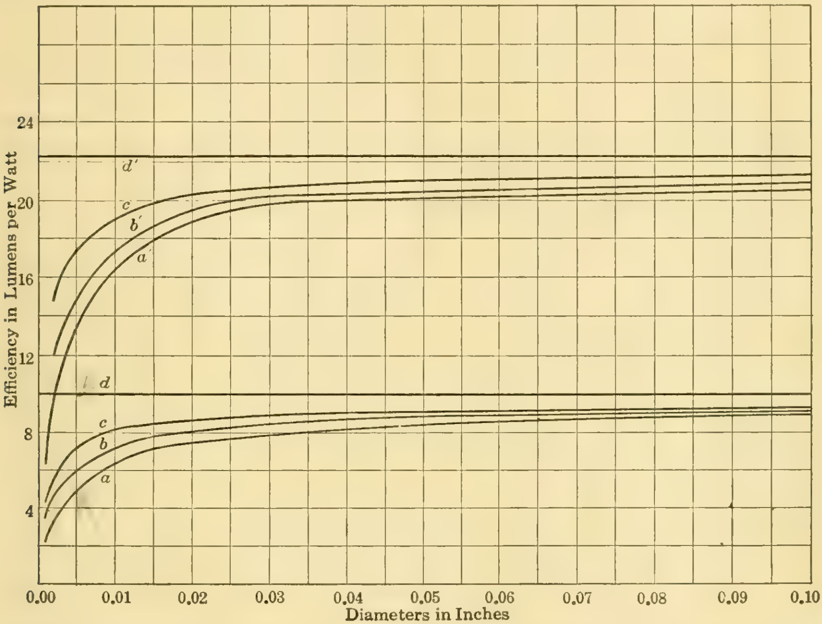


FIG. 31. Diagram Showing the Effects of the Gas Conduction and Convection Losses in Gas-filled Tungsten Lamps on their Efficiencies when Operated at 2445° K (the unprimed letters) and at 2885° K (primed letters) in Nitrogen (a, a'), Argon (b, b') and Mercury Vapor (c, c'), All at Atmospheric Pressure, as Compared with their Operation *in Vacuo* (d, d').

atmospheric pressure, gives efficiencies of 10 and 4.9 lumens per watt respectively. In order that the temperature and consequently the luminous flux shall be the same, the wattages supplied must be in the ratio of 1 to $\frac{100}{49}$ or of 1 to 2.04. In the nitrogen-filled lamp, the energy carried away by conduction and convection is slightly greater than that which is radiated. For a 50 mil (0.050 inch) filament under the same conditions the corresponding supply wattages vary as 1 to 1.18. The wattage loss due to gaseous conduction is only 18 per cent of the wattage needed for maintaining the radiation. In per cent, the gas loss for the

smaller filament is about 5.6 times that for the larger filament. Similar effects are to be noted in connection with argon and mercury vapor.

The differences in the percentage gas losses for different sized filaments are connected with the divergences in the stream paths of the heat conducted away. Consider two cylindrical filaments, respectively 1 mm. and 1 cm. in diameter. The stream paths for pure heat conduction, the main method by which heat energy is removed from the immediate neighborhoods of the filaments, are prolonged radii of the filaments. Relatively, they diverge rapidly from one another near the small filament and slowly near the large filament. The rates are as 10 to 1 per mm. of stream path. In a simple way, it may be said that each unit of heat energy conducted away from the small filament has a much larger space in which to be disposed of than has each unit from the large filament. From each element of surface of the smaller filament, heat is conducted away more rapidly than from an equal element of surface of the larger filament, and thus the percentage gas loss for the smaller filament is the greater.

An obvious way of reducing these losses, when the small filaments of common commercial lamps are used, is to form them into helix-shaped coils. Thus, in the commercial 75-watt, 110-volt, argon-filled lamp, where a 2.2-mil filament is formed into a coil with an 11-mil external diameter, the percentage gas loss as a first approximation is reduced by the coiling from that corresponding to a straight 2.2-mil filament in argon to that corresponding to a straight 11-mil filament in argon. At 2885° K., as shown by Fig. 31, the gas loss is thereby reduced from about 45 per cent to about 20 per cent of the input. There is a corresponding but not equal gain in efficiency. In effect, without greatly changing the size of a filament or of the current and voltage required for a lamp of given wattage, the gas loss is materially reduced. It might be expected that in practice the coil diameters could be made larger than they actually are and the gas loss still further reduced. Rigidity considerations, however, impose a limit from this point of view.

With increase in operating temperature, there is an increase in absolute amount both in the wattage necessary to maintain the radiation and in that necessary to offset the gas-conduction loss. However, that portion which maintains the radiation increases the more rapidly. In consequence the gas loss becomes relatively less important at the higher temperatures. Thus, for 5-mil and 50-mil filaments in nitrogen at 2885° K., according to Fig. 31, the gas losses are 66 per cent and 11 per cent, respectively, of the radiation rates, while at 2445° K., they are instead 102 per cent and 18 per cent.

In any particular lamp, there is justification from the efficiency viewpoint for the use of gas-filled lamps only when the percentage of energy lost by gaseous conduction is more than offset by the increased temperature and consequent increased efficiency gained by the reduced rate of vaporization.

Black-body Effect. — Gas-filled lamps are made with coiled filaments. Fig. 32 is a photograph of an incandescent coiled filament. It will be noted that the outsides of the turns of the helix are not as bright as the insides. Measurement with an optical pyrometer indicates that the insides of the coils are from 50 per cent to 100 per cent brighter than the outsides. This difference cannot be accounted for by the difference in filament temperature between the inside and the outside. It is due to the multiple reflection of the light within the helix and is commonly characterized as the black-body effect. The light from the inside is slightly more yellow than that from the outside, owing to this multiple reflection. This partially blackened radiation from the interior, for reasons illustrated in Fig. 27, is less efficient than that from the surface.

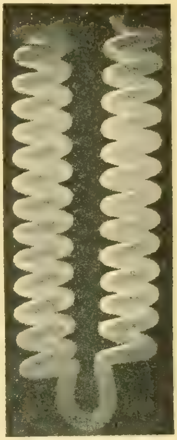


FIG. 32. Lighted Coil Filament.

The coiling of the lamp filament, therefore, while limiting certain gas losses, has cut down the favorable selectivity of the unit as a whole. Changes in coiling which lead to a reduction of blackening are to some extent opposed to changes which lead to reduced gas losses. Manufacturers naturally accept a compromise in their attempt to obtain the highest possible efficiency.

Light Distribution. — The quantity of light given off in different directions from the lamps depends upon the shape of the lamp filament, the shape of the bulb and the filament position in the bulb, and also on the character of the bulb surface. The reduction factor (see Chapter III) for the oval anchored carbon lamps averages about 0.82; for the straight-filament vacuum lamps, about 0.79; and for the coiled-filament gas-filled lamps from 0.75 to 1.00. The wide range in reduction factors obtained on gas-filled lamps shows the necessity of measuring the total light output rather than the mean horizontal candlepower as was the custom with vacuum lamps.

Temperatures and Efficiencies. — The radiation process in gas-filled lamps is the same as in vacuum lamps. The main and practically sole cause is temperature, and the principal difference in the two cases is resolvable into a difference in temperature. Whereas for vacuum lamps of the 115-volt class the temperature range is from about 2380° K.,

to 2460° K, in gas-filled lamps of the same class the range is from about 2650° K. to about 3100° K.

The spectral energy curves of gas-filled lamps compared with those from vacuum lamps have their centers shifted more toward the shorter wave-lengths, and therefore have a greater portion in the visible part of the spectrum. The same shift depending on filament size occurs among the gas-filled lamps themselves. It is exactly the same kind of shift that occurs in black-body radiation with change in temperature and is here, as in that case, the cause for a large part of the efficiency variations which occur.

Efficiency as a function of lamp wattage is shown in Fig. 33 for commercial lamps of the 115-volt class, for the vacuum and the gas-filled types. In each case, the operating condition is such as to give a life of 1000 hours. The efficiencies of the gas-filled lamps are seen to extend over a considerably greater range than do those of the vacuum lamps, a range of 10 to 20 $\frac{\text{lumens}}{\text{watt}}$ *vs.* 8 to 11 $\frac{\text{lumens}}{\text{watt}}$.

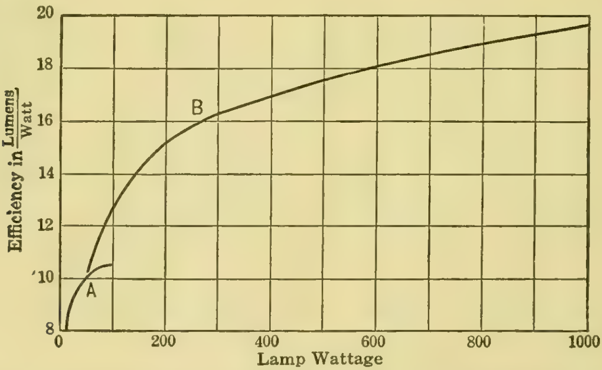


FIG. 33. Rated Efficiency of Vacuum (A) and Gas-filled (B) Tungsten Lamps of the 115-volt Class as Functions of Lamp Wattage.

The reason for the lower wattage limit for gas-filled lamps of the 115-volt class as well as the practical upper limit for vacuum lamps of the same class is shown in Fig. 33.

Color of Radiation. — Just as with black-body radiation, an increase in temperature for tungsten causes a progressively greater and greater increase in luminosity as one proceeds from the red end to the blue end of the spectrum and, as a whole, a less reddish or a more nearly white light. Though the gas-filled lamps represent a considerable approach to white light, they are still far from the standard of white-light sources, the sun. There is no hope of closely approaching the sun in color with

an incandescent tungsten filament without interposing a screen which relatively transmits but little at the red end of the spectrum in comparison with the blue end, as has been partially accomplished in the blue-bulb gas-filled lamp.

Design

The designer has at his disposal a large amount of experimental data and experience which guide him in the selection of materials and in their fabrication and arrangement into a successful lamp.

To produce the lamp best suited for a given service, the designer should know what the conditions of operation will be in that service, the voltage or current at which the lamp will be operated, the wattage desired, the limitations, if any, as regard light source or lamp dimensions, and the hours of life which the service requires.

Various classes of service justify the use of lamps designed to remain in service for quite different numbers of hours. For example, " street-series " lamps may justify a life of 1350 hours, locomotive headlight lamps 500 hours, motion-picture lamps 100 hours, automobile lamps 150 hours, flashlight lamps 9 hours, whereas the regular lamps used on central-station circuits are considered satisfactory if they average 1000 hours.

Filaments. — In general, the life of an incandescent filament lamp is dependent upon the operating temperature of the filament. The higher the filament temperature, the higher will be the operating efficiency and the shorter the life. Therefore, the number of hours of life fixes approximately the temperature at which the filament should operate. Knowing the amperes and volts of the lamp, one can select the correct diameter of filament wire and cut it to the proper length to meet these conditions in the finished lamp. The filament dimensions may be computed from the equations

$$(1) \quad W = MI^n$$

$$(2) \quad L = \frac{CWV}{I}$$

where W is the weight of the filament wire per unit length, I is the amperes required to heat the filament to a given temperature, V is the voltage to force the current, I, through a length, L, of filament wire and M, n, and C, are constants which depend upon the physical properties of the wire, its temperature, and its form in the lamp. Having once determined these constants for a given filament material and for a particular type of lamp, it is a simple matter to compute the proper

filament weight and length to produce a lamp of definite voltage and current values. The development of drawn-wire tungsten has opened up many new applications for incandescent lamps. The wire offers almost unlimited possibilities as regards the shape and size of the filament and the resultant shape and size of the finished lamps. Some lamps have been made with bulbs $\frac{1}{8}$ inch in diameter and $\frac{1}{4}$ inch long and with a consumption of a fraction of one watt; others have been made with bulbs 8 or 10 inches in diameter and with a consumption of several thousand watts. The filament size and shape and position in the bulb have an effect on the shape of light distribution from the finished lamp. If the requirements to be met are fully known, it is usually possible to produce a lamp to fit those requirements. In recent years an enormous amount of work has been done in the metallurgy of tungsten and the effect on various lamp characteristics of differences in crystal structure of filaments of tungsten. But this subject is too involved to come within the scope of this volume.

The whole structure of the lamp is built up around the filament; the other parts of the lamp are but servants that aid the filament in the fulfilment of its function as a light-producer. The relation of these parts to the filament operation will be considered next.

Supports. — The tungsten filament should be supported in such a manner that it is both electrically and thermally well insulated and that it will maintain its shape throughout life and not break under normal service conditions. Since fine tungsten filaments are rather fragile, the problem is a difficult one.

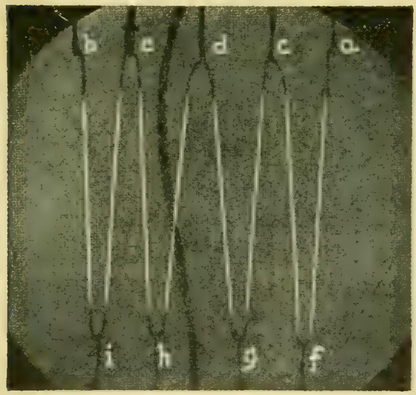


FIG. 34. Special Vacuum Lamp with Supports of Different Materials and Sizes.

Fig. 34 is a photograph of a lighted filament mounted specially to illustrate the cooling of the filament at supports in a vacuum lamp. The terminals, *a* and *b*, are 16-mil copper clamped to the ends of the filament; the supports, *c*, *d* and *e*, are 10-, 20- and 40-mil copper and the supports, *f*, *g*, *h* and *i*, are 4-, 8- and 16-mil molybdenum. The length of filament that is cooled depends upon the size and the material of the supports and the size and temperature of the filament. It will be noted that the filament in contact with copper is cooled for a greater length than that in contact with

molybdenum of the same size. There is also a noticeable difference in the length cooled by different sizes of molybdenum supports. The cooling of the filament is much less in the case of the 2-mil support.

In addition to low heat conductivity, the supports should have enough rigidity to hold the filament in shape and enough flexibility to take up most of the shock when the lamp is roughly handled.

Lead Wires. — The lead wires connect the ends of the filament to the lamp base. A proper choice involves consideration of both their electrical and thermal conductivities as well as their mechanical properties. It is desirable to keep the energy loss in the lead wires as low as is consistent with other features in lamp performance. The seal leads must make vacuum-tight joints with the glass. This limitation makes the seal the most important part of the lead wire. The materials to be used in leads, together with the dimensions of the parts, must be accurately specified to insure a successful lamp.

Glass Parts. — A number of different glasses have been produced which have slightly different qualities, and the designer must select the ones best suited for the requirements of the particular lamp he is designing. It is necessary to choose glass parts in any one lamp which will work together and not crack during the normal life of the lamp.

The lamp must be so designed that the glass parts will not exceed their safe operating temperature. The safe operating temperature may be far below the softening temperature of the glass.

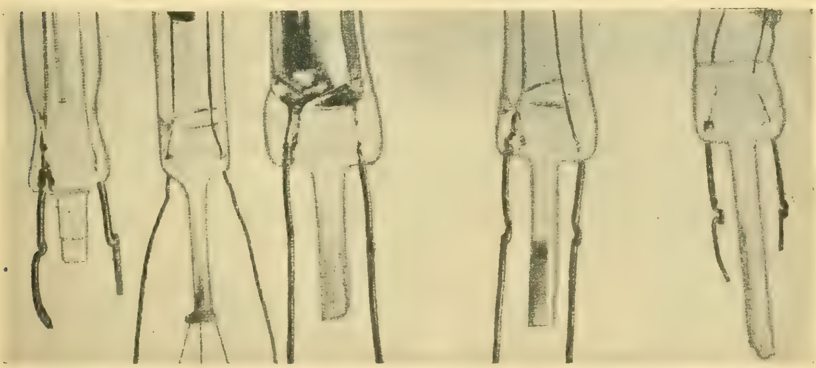


FIG. 35. Glass Stems from Gas-filled Lamps, Cracked as a Result of Electrolysis.

Figure 35 illustrates the effect of electrolysis in lamp stems. These stems were taken from lamps operated on direct current. The temperature of the glass was high enough to reduce the electrical resistance of the glass to the danger point. The glass gradually decomposed and

cracks developed which resulted in lamp failures due to admitting air into the bulbs.

The limit of bulb size in vacuum tungsten lamps is not usually the softening point of the glass. As the lamp progresses in life, the bulb gradually darkens, owing to the deposit formed on the bulb by the tungsten metal evaporated from the filament. The smaller the bulb, the denser will be this black coating and the poorer will be the lumen maintenance of the lamp. In practice, the designer chooses a bulb size that will give satisfactory candlepower maintenance from the standpoint of bulb darkening.

Bulb shapes in vacuum lamps are usually chosen for mechanical convenience in the manufacture of the lamps. The straight-sided bulb is the most common. Round- and tubular-bulb lamps are usually produced to meet some special requirement and are more difficult to make than the straight-sided bulb lamps. In vacuum lamps, the bulb darkening is distributed quite uniformly over the bulb surface; but in gas-filled lamps, the darkening on the bulbs is localized on account of the circulation of gas within the bulb. Since the shape of the bulbs in gas-filled lamps affects the distribution of the blackening, the designer is given an additional means of controlling the quality of lamps.

In gas-filled lamps, the bulb size is frequently limited by the softening of the glass. The hot gases heat the bulb locally and may blow a hole in it if the softening temperature is reached. Bulb sizes are in general much smaller for gas-filled lamps than for vacuum lamps of the same wattage, owing to the lower rate of filament evaporation in the gas-filled lamps. This has made possible the manufacture of lamps of much higher wattage than was feasible before the gas-filled lamp was developed.

Heat deflectors, consisting of mica disks, are often used in gas-filled lamps to protect the stem seal and the glass parts, forming the framework for supporting the filament, from the hot gases which would otherwise strike them.

Choice of Gas. — The necessity that the gas in which a tungsten filament is immersed shall not attack it chemically has thus far limited the gases seriously considered to nitrogen, argon and mercury vapor. Theory and experiment show that the gas conduction losses in different gases are proportional to the mobilities of the molecules; that is, to their velocities. Since the velocities which gaseous molecules possess at a given temperature are inversely proportional to the square roots of their atomic weights, one would expect that for these gases the order of preference would be mercury vapor, argon and nitrogen, their molecular weights being 200, 39.8 and 28.0. This is in accord with Fig. 31.

Theory and experiment show a change in the rate of vaporization of a filament with change in the immersing gas. The experimental result appears as a change in life for operation at some fixed temperature. Thus the life of a tungsten filament in nitrogen is only 80 per cent of what it is in argon. In other words, the rate of vaporization in argon is about 80 per cent of the rate in nitrogen. The heavier, slow-moving argon atoms offer the greater resistance to the diffusion of the tungsten atoms away from the thin layer of saturated tungsten vapor next to the hot filament. For the same average life, an argon atmosphere permits of a higher filament temperature and consequently also a greater luminous efficiency.

Both gas loss and vaporization considerations indicate mercury vapor to be the most desirable atmosphere. Unfortunately, the pressure of mercury vapor that is necessary in a gas-filled lamp with the filament heated is very much greater than its vapor tension at ordinary temperatures. Consequently, in such a lamp, most of the mercury is in liquid form when the lamp is not lighted. The time lag in vaporizing the liquid mercury when the lamp is lighted has such deleterious consequences, however, that the value of its other inherent advantages is minimized. Argon, the next most favorable gas from gas-loss and vaporization considerations, does not suffer from this disadvantage. It has in consequence been chosen for the atmosphere in gas-filled lamps. Commercial argon contains about 20 per cent nitrogen. Due to the low arcing potential of argon, some admixture of nitrogen seems necessary.

If a 100-watt vacuum construction lamp were filled with gas and burned base up, the upper portion of the filament would operate at a much higher temperature than the lower. A different mount design is required for the gas-filled lamp, to reduce the energy loss due to gas and to give a uniform filament temperature. This is accomplished by coiling the filament into a helix.

Coiled filaments have sometimes been used in vacuum lamps to secure greater filament concentration, but as a rule, the life performance is inherently poorer than for the straight-filament lamp, owing to the black-body effect obtained with the coiled filament. It is necessary to operate the coiled filament at a slightly higher temperature to produce a lamp with the same operating efficiency. It is more difficult to produce coiled filament lamps with uniform initial ratings than is the case with straight-filament lamps.

The design of lamps is by no means a cut-and-dried proposition. Much of the knowledge of materials, their preparation and use in lamps is still incomplete. Many of the changes in design suggested must be

thoroughly tested out before they can be made use of. It may happen that some seemingly insignificant change may produce a big effect and one entirely different from that expected. The question which the designer must continually face is "How will the lamp perform under actual service conditions?" He must submit the proposed lamps to tests which are even more severe than those likely to be met in practice.

Tables of Characteristic Relations for Tungsten Vacuum Incandescent Lamps

Explanation of Use of Tables. — The first step in the solution of every problem involving characteristic equations is to determine from the observed values of voltage, candlepower, and w.p.c. the corresponding values at normal efficiency, which for these tables was chosen at 1.20 w.p.c.

This is done by reference to Table XXIII, in which observed w.p.c. in steps of 0.1 and intermediate steps of 0.01 are given at the top and left margin, respectively. In the body of the table under "volts" and "cp.," respectively, are given the corresponding percentage factors by which the observed voltage and observed candlepower, respectively, are to be multiplied to reduce them to normal values. Normal wattage is found by multiplying normal candlepower by 1.20.

For example, if the observed values are 110 volts, 25 candles, 1.35 w.p.c., the corresponding normal values are found as follows: Corresponding to 1.35 w.p.c., find 106.0 under volts and 123.3 under cp. Then, $110 \times 1.060 = 116.6$ volts, $25 \times 1.233 = 30.82$ candles, and $30.82 \times 1.20 = 36.98$ watts, these being the normal values.

With these values known, read from one of the other three tables (viz., XXIV–XXVI) values corresponding to any desired percentage value of any one of the variables given.

The simplest problem is when values corresponding to a given voltage are required, because all three tables are arranged for voltage considered as the independent variable, and the other variables are given in the body of the table.

For example, assuming the normal values just found, suppose values for candlepower, wattage and w.p.c. corresponding to 125 volts are required. The voltage ratio $= 125 \div 116.6 = 107.2$ per cent. Corresponding to 107.2 per cent volts in Tables XXIV, XXV, and XXVI, find 128.1 per cent cp., 111.63 per cent watts, and 1.045 actual w.p.c., respectively. The numerical values corresponding to the two percentage values are found by multiplying each by the corresponding normal value as follows:

$1.281 \times 30.82 = 39.48$ candles, and $1.1163 \times 36.98 = 41.28$ watts.

Hence the corresponding values of all the variables are 125.0 volts, 39.48 candles, 41.28 watts and 1.045 w.p.c.

As a second problem, suppose that the values of voltage, wattage and w.p.c., corresponding to 20 candles, are required, the same normal values being assumed. This candlepower value is $20 \div 30.82 = 64.9$ per cent of normal. From 64.9 per cent cp. in the body of Table XXIV, find the corresponding voltage per cent at the top and margin — that is, $88.0 + (2.14 \div 2.67) = 88.8$ per cent volts. With this value known, find 82.846 per cent watts in Table XXV and 1.532 actual w.p.c. in Table XXVI. Multiplying percentage values by corresponding normal values, $0.888 \times 116.6 = 103.5$ volts, and $0.82846 \times 36.98 = 30.64$ watts. The variables are, therefore, 20.0 candles, 103.5 volts, 30.64 watts and 1.532 w.p.c.

In the same manner, values for all the variables corresponding to a given value of wattage or of w.p.c. may be found also.

A third problem of importance to the testing laboratory involves the reduction of voltage, candlepower and wattage from observed values to values they would have at some given w.p.c. (For example, a w.p.c. at which the lamps are to be run on life test.) The calculation of voltage is the one of most importance, the other variables being usually neglected in life-test calculations.

Example. — Given 110 volts, 88 candles, 1.05 w.p.c.; required volts, candles and watts at 0.7 w.p.c.

Solution. — In Table XXIII, find at 1.05 w.p.c. 93.49 per cent volts and 78.66 per cent candles, and at 0.7 w.p.c. 75.26 per cent volts and 37.23 per cent candles. Then at 0.7 w.p.c.

$$\text{volts} = \frac{110 \times 93.49}{75.26} = 136.6$$

$$\text{candles} = \frac{88 \times 78.66}{37.23} = 185.93$$

$$\text{watts} = 185.93 \times 0.7 = 130.15.$$

Reduction of Values to a w.p.c. Basis Other Than 1.20. — If some other w.p.c. than 1.20 be chosen as normal, tables of values can be readily determined from these tables by any of the three following methods:

(*a*) Suppose, for example, that 1.10 w.p.c. is chosen as normal. Corresponding to 1.10 in Table XXVI, find 104.48 per cent volts. Corresponding to 104.48 per cent volts in Tables XXIV and XXV, find 116.9 per cent cp. and 107.18 per cent watts, respectively. Therefore,

the values in the present tables corresponding to normal in the new tables are as follows: 104.48 per cent volts, 116.9 per cent cp., 107.18 per cent watts, and 1.10 actual w.p.c.

Now, suppose, for example, that values at 115.0 per cent volts on the new basis are required. Voltage ratio is then $115.0 \times 1.0448 = 120.15$ per cent. Corresponding to 120.15 per cent volts in Tables XXIV, XXV and XXVI, find 190.7 per cent cp., 133.66 per cent watts, and 0.8412 actual w.p.c., respectively.

Hence, corresponding to 115.0 per cent volts, the new tables:

$$\begin{aligned} 120.15 \div 1.0448 &= 115.0 \text{ per cent volts,} \\ 190.7 \div 1.169 &= 163.1 \text{ per cent candles,} \\ 133.66 \div 1.0718 &= 124.71 \text{ per cent watts,} \\ \text{and} \quad 0.8412 &= \text{actual w.p.c.} \end{aligned}$$

In the same manner, values corresponding to other percentage values of voltage may be found, and a complete set of tables corresponding to Tables XXIV, XXV and XXVI, on the new basis, may be constructed.

Values for Table XXIII are obtained by dividing the tabulated values of the factors designated " volts " by 0.9573 and those designated " cp." by 0.8554, these being the values at 1.10 w.p.c. For example, the tabulated values of " volts " and " cp." at 1.00 w.p.c. in Table XXIII are 91.17 and 72.00, respectively. Values for the new table are then

$$\frac{91.17}{0.9573} = 95.24 \text{ " volts " } \quad \text{and} \quad \frac{72.00}{0.8554} = 84.17 \text{ " cp."}$$

(*b*) Values corresponding to each point in Tables XXIV, XXV and XXVI need not necessarily be computed as given above. A simple method is to compute values at points, say, 5 or 10 per cent apart in voltage (for example, 80, 85, 90, 95, etc.) and take differences between the values obtained and those given in the tables. Then, with per cent volts as ordinates and differences as abscissas, a smooth curve may be drawn through the points found, and from it the difference at any per cent volts may be read. These differences added to the tabulated values give values for the new tables.

Tables of Characteristic Relations

TABLE XXIII

Table of percentage multiplying factors for reducing observed values of voltage and observed values of candlepower at known w.p.c. to values they would have at 1.20 w.p.c. Voltage factors are indicated by " Volts "; candlepower factors by " Cp."

Example: Given as observed values, 112.0 volts, 16.0 candles, 1.450 w.p.c., to find volts and candles at 1.20 w.p.c.

Solution: Corresponding to 1.450 w.p.c. find 109.7, the voltage percentage multiplier, and 139.9, the candlepower percentage multiplier. The values corresponding to 1.20 w.p.c. are, therefore, 112.0 × 1.097 = 122.86 volts, and 16.0 × 1.399 = 22.38 candles.

Obs. w.p.c.	0.70				0.80				0.90			
	Volts	Dif.	Cp.	Dif.	Volts	Dif.	Cp.	Dif.	Volts	Dif.	Cp.	Dif.
0.00	75.26		37.23		81.01		47.79		86.29		59.40	
		0.60		1.01		0.55		1.11		0.50		1.21
.01	75.86		38.24		81.56		48.90		86.79		60.61	
		.59		1.02		.54		1.13		.50		1.23
.02	76.45		39.26		82.10		50.03		87.29		61.84	
		.59		1.03		.54		1.13		.50		1.23
.03	77.04		40.29		82.64		51.16		87.79		63.07	
		.58		1.04		.53		1.15		.49		1.25
.04	77.62		41.33		83.17		52.31		88.28		64.32	
		.58		1.05		.53		1.16		.49		1.25
.05	78.20		42.38		83.70		53.47		88.77		65.57	
		.57		1.06		.53		1.17		.49		1.27
.06	78.77		43.44		84.23		54.64		89.26		66.84	
		.57		1.07		.52		1.17		.48		1.27
.07	79.34		44.51		84.75		55.81		89.74		68.11	
		.56		1.09		.52		1.19		.48		1.29
.08	79.90		45.60		85.27		57.00		90.22		69.40	
		.56		1.09		.51		1.19		.48		1.29
.09	80.46		46.69		85.78		58.19		90.70		70.69	
		.55		1.10		.51		1.21		.47		1.31
.10	81.01		47.79		86.29		59.40		91.17		72.00	

Obs. w.p.c.	1.00				1.10				1.20			
0.00	91.17		72.00		95.73		85.54		100.0		100.0	
		0.47		1.31		0.44		1.41		0.4		1.5
.01	91.64		73.31		96.17		86.95		100.4		101.5	
		.47		1.32		.43		1.41		.4		1.5
.02	92.11		74.63		96.60		88.36		100.8		103.0	
		.46		1.33		.44		1.42		.4		1.5
.03	92.57		75.96		97.04		89.78		101.2		104.5	
		.46		1.35		.43		1.44		.4		1.5
.04	93.03		77.31		97.47		91.22		101.6		106.0	
		.46		1.35		.43		1.44		.4		1.6
.05	93.49		78.66		97.90		92.66		102.0		107.6	
		.45		1.36		.42		1.45		.4		1.5
.06	93.94		80.02		98.32		94.11		102.4		109.1	
		.45		1.36		.43		1.46		.4		1.5
.07	94.39		81.38		98.75		95.57		102.8		110.6	
		.45		1.38		.42		1.47		.4		1.6
.08	94.84		82.76		99.17		97.04		103.2		112.2	
		.45		1.38		.42		1.47		.4		1.6
.09	95.29		84.14		99.59		98.51		103.6		113.8	
		.44		1.40		.41		1.49		.4		1.5
.10	95.73		85.54		100.00		100.00		104.0		115.3	

TABLE XXIII. — *Continued*

Obs. w.p.c.	1.30				1.40				1.50			
	Volts	Dif.	Cp.	Dif.	Volts	Dif.	Cp.	Dif.	Volts	Dif.	Cp.	Dif.
0.00	104.0		115.3		107.8		131.5		111.5		148.5	
		0.4		1.6		0.4		1.6		0.3		1.7
.01	104.4		116.9		108.2		133.1		111.8		150.2	
		.4		1.6		.4		1.7		.4		1.8
.02	104.8		118.5		108.6		134.8		112.2		152.0	
		.4		1.6		.4		1.7		.3		1.7
.03	105.2		120.1		109.0		136.5		112.5		153.7	
		.4		1.6		.3		1.7		.4		1.8
.04	105.6		121.7		109.3		138.2		112.9		155.5	
		.4		1.6		.4		1.7		.3		1.8
.05	106.0		123.3		109.7		139.9		113.2		157.3	
		.4		1.6		.3		1.7		.4		1.8
.06	106.4		124.9		110.0		141.6		113.6		159.1	
		.4		1.6		.4		1.7		.3		1.8
.07	106.8		126.5		110.4		143.3		113.9		160.9	
		.3		1.7		.4		1.7		.4		1.8
.08	107.1		128.2		110.8		145.0		114.3		162.7	
		.4		1.6		.3		1.8		.3		1.8
.09	107.5		129.8		111.1		146.8		114.6		164.5	
		.3		1.7		.4		1.7		.4		1.8
.10	107.8		131.5		111.5		148.5		115.0		166.3	

Obs. w.p.c.	1.60				1.70				1.80			
0.00	115.0		166.3		118.3		184.8		121.4		204.1	
		0.3		1.8		0.3		1.9		0.4		2.0
.01	115.3		168.1		118.6		186.7		121.8		206.1	
		.3		1.8		.3		1.9		.3		1.9
.02	115.6		169.9		118.9		188.6		122.1		208.0	
		.4		1.9		.3		1.9		.3		2.0
.03	116.0		171.8		119.2		190.5		122.4		210.0	
		.3		1.8		.4		1.9		.3		2.0
.04	116.3		173.6		119.6		192.4		122.7		212.0	
		.3		1.8		.3		2.0		.3		2.0
.05	116.6		175.4		119.9		194.4		123.0		214.0	
		.4		1.9		.3		1.9		.3		2.0
.06	117.0		177.3		120.2		196.3		123.3		216.0	
		.3		1.9		.3		1.9		.3		2.0
.07	117.3		179.2		120.5		198.2		123.6		218.0	
		.3		1.8		.3		2.0		.3		2.0
.08	117.6		181.0		120.8		200.2		123.9		220.0	
		.3		1.9		.3		2.0		.3		2.1
.09	117.9		182.9		121.1		202.2		124.2		222.1	
		.4		1.9		.3		1.9		.3		2.0
.10	118.3		184.8		121.4		204.1		124.5		224.1	

TABLE XXIII. — *Continued*

Obs. w.p.c.	1.90				2.00				2.10			
	Volts	Dif.	Cp.	Dif.	Volts	Dif.	Cp.	Dif.	Volts	Dif.	Cp.	Dif.
0.00	124.5		224.1		127.4		244.9		130.3		266.3	
		0.3		2.1		0.3		2.1		0.3		2.2
.01	124.8		226.2		127.7		247.0		130.6		268.5	
		.3		2.0		.3		2.2		.2		2.2
.02	125.1		228.2		128.0		249.2		130.8		270.7	
		.3		2.1		.3		2.1		.3		2.2
.03	125.4		230.3		128.3		251.3		131.1		272.9	
		.3		2.0		.3		2.2		.3		2.2
.04	125.7		232.3		128.6		253.5		131.4		275.1	
		.3		2.1		.3		2.1		.2		2.3
.05	126.0		234.4		128.9		255.6		131.6		277.4	
		.3		2.1		.2		2.2		.3		2.2
.06	126.3		236.5		129.1		257.8		131.9		279.6	
		.3		2.1		.3		2.1		.3		2.2
.07	126.6		238.6		12. .4		259.9		132.2		281.8	
		.3		2.1		.3		2.1		.3		2.2
.08	126.9		240.7		129.7		262.0		132.5		284.0	
		.3		2.1		.3		2.2		.2		2.2
.09	127.2		242.8		130.0		264.2		132.7		286.2	
		.2		2.1		.3		2.1		.3		2.2
.10	127.4		244.9		130.3		266.3		133.0		288.4	

Obs. w.p.c.	2.20				2.30				2.40			
0.00	133.0		288.4		135.7		311.1		138.3		334.5	
		0.3		2.2		0.2		2.3		0.2		2.4
.01	133.3		290.6		135.9		313.4		138.5		336.9	
		.3		2.3		.3		2.4		.3		2.4
.02	133.6		292.9		136.2		315.8		138.8		339 3	
		.2		2.3		.3		2.4		.2		2.4
.03	133.8		295.2		136.5		318.2		139.0		341.7	
		.3		2.3		.2		2.3		.3		2.4
.04	134.1		297.5		136.7		320.5		139.3		344.1	
		.3		2.3		.3		2.3		.2		2.4
.05	134.4		299.8		137.0		322.8		139.5		346.5	
		.2		2.2		.2		2.4		.3		2.4
.06	134.6		302.0		137.2		325.2		139.8		348.9	
		.3		2.3		.3		2.3		.2		2.4
.07	134.9		304.3		137.5		327.5		140.0		351.3	
		.3		2.3		.3		2.3		.3		2.4
.08	135.2		306.6		137.8		329.8		140.3		353.7	
		.2		2.3		.2		2.4		.2		2.4
.09	135.4		308.9		138.0		332.2		140.5		356.1	
		.3		2.2		.3		2.3		.3		2.4
.10	135.7		311.1		138.3		334.5		140.8		358.5	

TABLE XXIII. — *Continued*

Obs. w.p.c.	2.50				2.60				2.70			
	Volts	Dif.	Cp.	Dif.	Volts	Dif.	Cp.	Dif.	Volts	Dif.	Cp.	Dif.
0.00	140.8		358.5		143.2		383.2		145.6		408.5	
		0.2		2.5		0.2		2.5		0.2		2.6
.01	141.0		361.0		143.4		385.7		145.8		411.1	
		.3		2.5		.3		2.5		.2		2.5
.02	141.3		363.5		143.7		388.2		146.0		413.6	
		.2		2.4		.2		2.6		.3		2.6
.03	141.5		365.9		143.9		390.8		146.3		416.2	
		.2		2.5		.2		2.5		.2		2.6
.04	141.7		368.4		144.1		393.3		146.5		418.8	
		.3		2.5		.3		2.5		.2		2.6
.05	142.0		370.9		144.4		395.8		146.7		421.4	
		.2		2.4		.2		2.6		.3		2.6
.06	142.2		373.3		144.6		398.4		147.0		424.0	
		.3		2.5		.3		2.5		.2		2.6
.07	142.5		375.8		144.9		400.9		147.2		426.6	
		.2		2.5		.2		2.5		.2		2.6
.08	142.7		378.3		145.1		403.4		147.4		429.2	
		.3		2.4		.2		2.5		.2		2.6
.09	143.0		380.7		145.3		405.9		147.6		431.8	
		.2		2.5		.3		2.6		.3		2.6
.10	143.2		383.2		145.6		408.5		147.9		434.4	

Obs. w.p.c.	2.80				2.90				3.00			
0.00	147.9		434.4		150.1		460.8		152.3		487.8	
		0.2		2.6		0.2		2.7		0.3		2.8
.01	148.1		437.0		150.3		463.5		152.6		490.6	
		.2		2.6		.3		2.7		.2		2.7
.02	148.3		439.6		150.6		466.2		152.8		493.3	
		.3		2.7		.2		2.7		.2		2.7
.03	148.6		442.3		150.8		468.9		153.0		496.0	
		.2		2.6		.2		2.7		.2		2.8
.04	148.8		444.9		151.0		471.6		153.2		498.8	
		.2		2.7		.2		2.7		.2		2.7
.05	149.0		447.6		151.2		474.3		153.4		501.5	
		.2		2.6		.2		2.7		.2		2.8
.06	149.2		450.2		151.4		477.0		153.6		504.3	
		.2		2.6		.3		2.7		.2		2.7
.07	149.4		452.8		151.7		479.7		153.8		507.0	
		.3		2.7		.2		2.7		.2		2.8
.08	149.7		455.5		151.9		482.4		154.0		509.8	
		.2		2.6		.2		2.7		.2		2.8
.09	149.9		458.1		152.1		485.1		154.2		512.6	
		.2		2.7		.2		2.7		.2		2.8
.10	150.1		460.8		152.3		487.8		154.4		515.4	

TABLE XXIII. — *Concluded*

Obs. w.p.c.	3.10				3.20			
	Volts	Dif.	Cp.	Dif.	Volts	Dif.	Cp.	Dif.
0.00	154.4		515.4		156.5		543.5	
		0.2		2.7		0.2		2.8
.01	154.6		518.1		156.7		546.3	
		.2		2.8		.2		2.9
.02	154.8		520.9		156.9		549.2	
		.2		2.8		.2		2.8
.03	155.0		523.7		157.1		552.0	
		.3		2.8		.2		2.9
.04	155.3		526.5		157.3		554.9	
		.2		2.8		.3		2.9
.05	155.5		529.3		157.6		557.8	
		.2		2.9		.2		2.9
.06	155.7		532.2		157.8		560.7	
		.2		2.8		.2		2.8
.07	155.9		535.0		158.0		563.5	
		.2		2.9		.2		2.9
.08	156.1		537.9		158.2		566.4	
		.2		2.8		.2		2.9
.09	156.3		540.7		158.4		569.3	
		.2		2.8		.2		2.9
.10	156.5		543.5		158.6		572.2	

TABLE XXIV

Table for aetermining values of candlepower corresponding to observed values of voltage, when the values of both candlepower and voltage at 1.20 w.p.c. are known. All values in this table are expressed in per cent.

Example: Given 125.0 volts and 34.0 candles, both at 1.20 w.p.c., to find candles at 100.0 volts.

Solution: 100.0 volts = 80 per cent of 125.0 volts. Corresponding to 80 per cent volts find in the table 43.95 per cent candles. Therefore, candles at 125.0 volts = 43.95 per cent of 34.0 = 14.94.

Obs. volts	60		70		80		90	
	Cp.	Dif.	Cp.	Dif.	Cp.	Dif.	Cp.	Dif.
0	14.34		26.35		43.95		68.18	
		0.98		1.49		2.11		2.83
1	15.32		27.84		46.06		71.01	
		1.03		1.55		2.18		2.90
2	16.35		29.39		48.24		73.91	
		1.07		1.61		2.24		2.98
3	17.42		31.00		50.48		76.89	
		1.12		1.66		2.31		3.05
4	18.54		32.66		52.79		79.94	
		1.18		1.73		2.39		3.14
5	19.72		34.39		55.18		83.08	
		1.22		1.79		2.45		3.22
6	20.94		36.18		57.63		86.30	
		1.28		1.85		2.53		3.30
7	22.22		38.03		60.16		89.60	
		1.33		1.91		2.60		3.38
8	23.54		39.94		62.76		92.98	
		1.38		1.97		2.67		3.47
9	24.92		41.91		65.43		96.45	
		1.43		2.04		2.75		3.55
10	26.35		43.95		68.18		100.00	

Obs. volts	100		110		120		130	
	Cp.	Dif.	Cp.	Dif.	Cp.	Dif.	Cp.	Dif.
0	100.0		140.3		189.9		249.5	
		3.6		4.5		5.5		6.5
1	103.6		144.8		195.4		256.0	
		3.8		4.6		5.6		6.6
2	107.4		149.4		201.0		262.6	
		3.8		4.8		5.7		6.8
3	111.2		154.2		206.7		269.4	
		3.9		4.8		5.8		
4	115.1		159.0		212.5			
		3.9		4.9		5.9		
5	119.0		163.9		218.4			
		4.1		5.0		6.0		
6	123.1		168.9		224.4			
		4.2		5.1		6.1		
7	127.3		174.0		230.5			
		4.2		5.2		6.2		
8	131.5		179.2		236.7			
		4.4		5.3		6.3		
9	135.9		184.5		243.0			
		4.4		5.4		6.5		
10	140.3		189.9		249.5			

TABLE XXV

Table for determining values of wattage corresponding to observed values of voltage when the values of both wattage and voltage at 1.20 w.p.c. are known. All values in this table are expressed in per cent.

Example: Given 98.0 watts and 110.0 volts, both at 1.20 w.p.c., to find watts at 90.2 volts.

Solution: 90.2 volts = 82 per cent of 110.0 volts. Corresponding to 82 per cent, find in the table 73.007 per cent watts. Therefore, watts at 90.2 volts = 73.007 per cent of 98.0 = 71.55 watts.

Obs. volts	60		70		80		90	
	Watts	Dif.	Watts	Dif.	Watts	Dif.	Watts	Dif.
0	44.406		56.772		70.200		84.628	
		1.187		1.295		1.399		1.495
1	45.593		58.067		71.599		86.123	
		1.198		1.307		1.408		1.505
2	46.791		59.374		73.007		87.628	
		1.209		1.317		1.419		1.514
3	48.000		60.691		74.426		89.142	
		1.220		1.328		1.428		1.524
4	49.220		62.019		75.854		90.666	
		1.231		1.338		1.438		1.533
5	50.451		63.357		77.292		92.199	
		1.243		1.348		1.448		1.542
6	51.694		64.705		78.740		93.741	
		1.253		1.359		1.458		1.551
7	52.947		66.064		80.198		95.292	
		1.264		1.368		1.467		1.560
8	54.211		67.432		81.665		96.852	
		1.275		1.379		1.477		1.570
9	55.486		68.811		83.142		98.422	
		1.286		1.389		1.486		1.578
10	56.772		70.200		84.628		100.000	

Obs. volts	100		110		120		130	
	Watts	Dif.	Watts	Dif.	Watts	Dif.	Watts	Dif.
0	100.00		116.27		133.40		151.35	
		1.59		1.68		1.76		1.84
1	101.59		117.95		135.16		153.19	
		1.60		1.68		1.77		1.85
2	103.19		119.63		136.93		155.04	
		1.60		1.69		1.77		1.85
3	104.79		121.32		138.70		156.89	
		1.61		1.70		1.79		
4	106.40		123.02		140.49			
		1.63		1.71		1.79		
5	108.03		124.73		142.28			
		1.63		1.72		1.80		
6	109.66		126.45		144.08			
		1.64		1.72		1.80		
7	111.30		128.17		145.88			
		1.65		1.74		1.82		
8	112.95		129.91		147.70			
		1.65		1.74		1.82		
9	114.60		131.65		149.52			
		1 67		1.75		1.83		
10	116.27		133.40		151.35			

TABLE XXVI

Table for determining watts per candle corresponding to observed voltage when the latter is expressed in per cent of the voltage at 1.20 w.p.c.

Example: Given 115.0 volts at 1.20 w.p.c., to find watts per candle corresponding to 96.6 volts.

Solution: 96.6 volts = 84.0 per cent of 115.0 volts. Corresponding to 84 per cent volts, find in the table 1.724, the w.p.c. required.

Obs. volts	60		70		80		90	
	W.p.c.	Dif.	W.p.c.	Dif.	W.p.c.	Dif.	W.p.c.	Dif.
0	3.716		2.585		1.916		1.490	
		0.145		0.083		0.051		0.034
1	3.571		2.502		1.865		1.456	
		.136		.078		.049		.033
2	3.435		2.424		1.816		1.423	
		.129		.075		.047		.032
3	3.306		2.349		1.769		1.391	
		.121		.071		.045		.030
4	3.185		2.278		1.724		1.361	
		.115		.067		.043		.029
5	3.070		2.211		1.681		1.332	
		.108		.065		.041		.028
6	2.962		2.146		1.640		1.304	
		.102		.061		.040		.028
7	2.860		2.085		1.600		1.276	
		.097		.059		.038		.026
8	2.763		2.026		1.562		1.250	
		.091		.056		.037		.026
9	2.672		1.970		1.525		1.224	
		.087		.054		.035		.024
10	2.585		1.916		1.490		1.200	

Obs. volts	100		110		120		130	
	W.p.c.	Dif.	W.p.c.	Dif.	W.p.c.	Dif.	W.p.c.	Dif.
0	1.200		0.9945		0.8431		0.7280	
		0.024		0.0172		0.0130		0.0098
1	1.176		.9773		.8301		.7182	
		.023		.0167		.0126		.0098
2	1.153		.9606		.8175		.7084	
		.022		.0163		.0122		.0095
3	1.131		.9443		.8053		.6989	
		.021		.0157		.0119		
4	1.110		.9286		.7934			
		.021		.0153		.0116		
5	1.089		.9133		.7818			
		.020		.0149		.0113		
6	1.069		.8984		.7705			
		.020		.0144		.0110		
7	1.049		.8840		.7595			
		.018		.0140		.0108		
8	1.031		.8700		.7487			
		.019		.0136		.0105		
9	1.012		.8564		.7382			
		.0175		.0133		.0102		
10	0.9945		.8431		.7280			

Vapor-tube Lamps

[L. J. Buttolph]

About 1850, Geissler began making the familiar gas-filled tubes known by his name, and in 1872, Sir William Crookes began his famous observations on the electric discharge through gases and through high vacua.

The Geissler and Crookes tubes, however, never got beyond the size of the little spectrum tubes so common to-day until, following closely after the lectures and striking demonstrations of Nicola Tesla in 1891, Dr. D. McFarlan Moore began his well-known researches in the development of a practical gaseous conductor lamp. He tested a large number of designs and used in them all possible gases and a great many vapors. The ones most commercially successful have been the relatively low-voltage, long-tube, nitrogen or carbon-dioxide filled lamps. The former yielded yellow-orange tinted light, the latter, white. With the former, in the long tube where the potential drops at the electrodes were relatively a small part of the whole, efficiencies of 6 lumens per watt were attainable; with the latter, 2 lumens per watt. Previous to the use of tungsten filament lamps, they compared favorably in efficiency with the incandescent lamps in use. But with the attainment of efficiencies of the order of 10 lumens per watt in the tungsten lamp, they were doomed as commercial sources for general illumination. However, where accurate color matching of objects is of interest, the carbon-dioxide filled tube still finds a commercial application. For this kind of work, moderate-sized units have been developed.

A gaseous pressure of the order of that due to 0.1 mm. of mercury was found to give the most satisfactory results. In order to maintain this pressure, an ingenious device was developed which automatically feeds carbon-dioxide into the tube when needed. It is, of course, necessary to use a transformer with the tube. The voltage necessary depends largely upon the length of the tube and is usually several thousand volts. The mechanical difficulty of building these tubes, some of them over a hundred feet in length, *in situ*, limited them to certain fields of novelty lighting.

Neon Tube. — More recently, in 1911, there was developed the neon tube which works on the same principle as does the Moore tube. It has the advantage of a higher efficiency and of greater permanency of operating condition. The gas does not disappear as rapidly with the continued use of the tube, probably because neon is one of the inert gases. Its great drawback lies in the cost of procuring the neon.

Still more recently, particularly in certain European countries, where higher-voltage circuits are more common than in the United States, 220-volt vacuum discharge tubes have attained considerable use. Low candlepower neon-vapor lamps, as they are called, are being made, however, for circuits with potential differences as low as 110 volts alternating current or 150 volts direct current. Since the maximum potential difference in an alternating current circuit determines the ability of the applied electromotive force in starting a discharge, it is seen that the basis for the two voltage ratings is the same. The wattage, candlepower and efficiencies for these lamps are all low. The orange-colored light is quite pleasing to the eye. It seems to have a field where only very small candlepower, small wattage sources are desired, and where decorative effects are an object, regardless of luminous efficiency obtained.

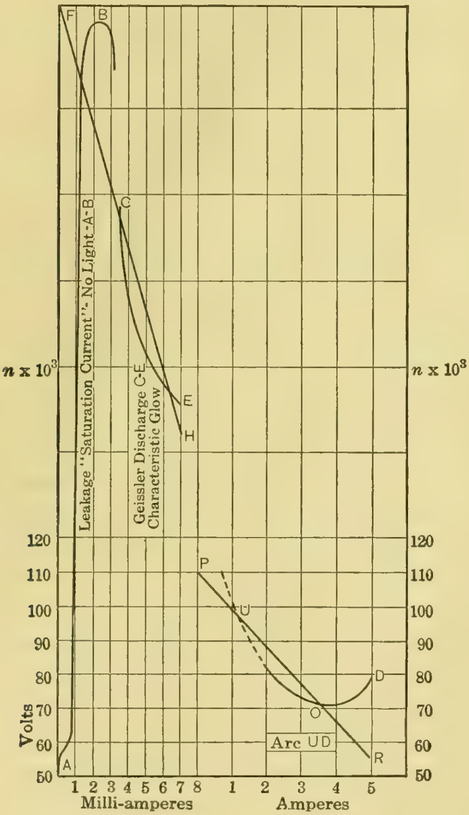


FIG. 36. Volt-Ampere Characteristics of a Mercury Geissler Tube and a Mercury Vapor Arc.

Mercury Vapor. — Geissler tubes containing mercury vapor can be operated by an induction coil giving a high voltage and high frequency. The resulting light is the familiar luminescence of mercury vapor. Closely related to this mercury Geissler tube is the mercury-vapor arc which gives the same characteristic luminescent light but differs from a Geissler tube in its electrical characteristics since it operates at relatively low voltage. The relationship between the volt-ampere characteristics of a mercury Geissler tube and of a mercury-vapor arc is approximately as shown in Fig. 36 where AB represents the leakage between electrodes at high voltages, CE the ordinary Geissler discharge at several thousand volts,

and UD an arc at low voltage. To correct the falling voltage characteristics of the Geissler discharge and of the arc, ohmic resistance is connected in series with the tubes. This resistance, 10 ohms for the arc, is represented by the slope of the line PR. A resistance of the order of 10^5 ohms for a Geissler tube is indicated by the slope of the line FH.

The Cooper-Hewitt mercury-vapor lamp was first exhibited in 1901. Since that time a great variety of designs have been tested out and the sizes have ranged from a few watts to 3000 watts. The present standard lamps range in size from 200 watts to 1600 watts. The largest, some of them 6 feet long by 3 inches in diameter, are principally used in blue-printing machines. The standard tubes for industrial illumination have a luminous tube 1 inch in diameter and 50 inches long. As shown in Fig. 46 they consist of a tube of glass containing mercury, mercury vapor and wires sealed into the ends of the tube and attached to a cathode electrode of metallic mercury and a cup-shaped anode electrode of iron to conduct electricity to and from the current-carrying vapor. Before a further description of the mercury-vapor lamp is given, the physics of the vacuum-tube discharge, of which the former is a specific case, will be discussed.

Physics of Vacuum-tube Discharge

Structure. — A simple form of vacuum-tube consists of a piece of glass tubing with lead wires passing through its sealed ends to metal terminals considerably separated. They are usually evacuated to pressures of the order of that due to a millimeter of mercury. The necessary voltages for starting and maintaining self-sustaining discharges are ordinarily obtained with transformers, induction coils, or any other source of high-voltage, alternating current or direct current. Discharges under suitable conditions, however, may be started and maintained on ordinary lighting circuits.

The structure of a discharge depends upon various factors, e.g., the residual gas, its pressure, the electrodes, their separation, the type of discharge. Fig. 37 (*a* and *b*) shows characteristic appearances for self-sustaining discharges. Beginning at the cathode, *c*, there are in order: (1) a bright, thin, luminous layer, the cathode glow; (2) a moderate-sized Crooke dark space; (3) an extended, bright negative glow; (4) a broad Faraday dark space; (5) a luminous positive column; (6) a narrow dark space; and (7) a thin, luminous anode layer. Layers (1), (2) and (3) are sometimes referred to as the three cathode layers, or merely as the cathode layer. Depending on conditions, the positive

column may be continuous or broken up into alternate dark and bright striæ. The boundaries of the luminous portions are relatively sharp on the cathode side and diffuse on the anode side.

The dimensions of the different parts of a discharge vary with the nature of the gas, its pressure and the nature of the electrodes. Starting with a discharge such as is shown in Fig. 37 (*a*), further decrease in pressure in the normal discharge (see page 136) results in approximately equal relative broadenings of the three cathode layers and of the Fara-

FIG. 37. Structure of Self-sustaining Vacuum-tube Discharges. *a* — Striated. *b* — Unstriated.

day dark space, and in the spreading and snuffing out of the positive column at the anode. The variation in the normal discharge approximately fits in with the assumption that between any characteristic surface in the discharge (e.g., front edge of negative glow or front edge of positive column) and the cathode, the same fixed number of gas molecules are to be found. This process may be continued up to the point where the positive column (but not the anode glow), the Faraday dark space, and a considerable part of the negative glow are snuffed out, the anode being immersed in the latter.

At higher pressures, the structure of a glow discharge is probably not essentially changed. At best, however, one is able only to discern three parts, the cathode layer, the Faraday dark space, and the positive column.

Potential Distribution. — Potential gradients or field strength, in volts per centimeter, found in certain instances for striated and unstriated discharges like those of Fig. 37 (*a* and *b*), are shown in Figs. 38 and 39. In the Crooke dark space, the potential gradient is very great. Toward the anode, it decreases rapidly, reaches a minimum just within the negative glow, rises again slowly in the Faraday dark space to the practically constant value of the unstriated positive column

or to the succession of slightly different maxima and minima of the striated positive column which, except for a small drop in potential just in front of the anode, reaches up to it practically unchanged.

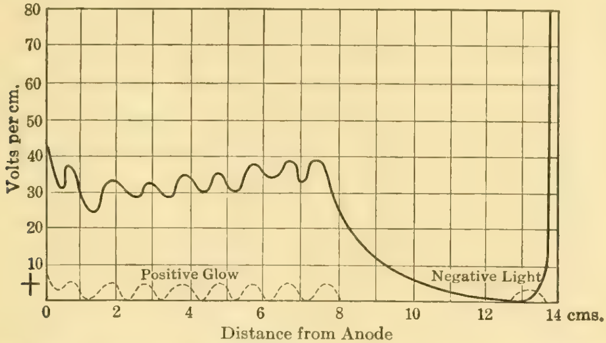


FIG. 38. Potential Gradient Variations in a Striated Discharge.

Integration of the potential gradient curves with respect to distance along the path of the discharge gives directly the drop in potential as a function of the distance from the anode or cathode. Thus Fig. 40, obtained by integration from Fig. 38, shows the potential variations in

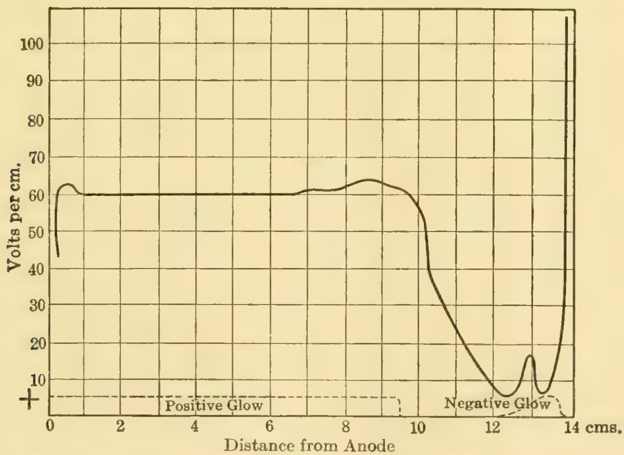


FIG. 39. Potential Gradient Variations in an Unstriated Discharge.

a particular striated discharge over the cathode glow and the Crooke dark space. The potential drop, usually referred to as the cathode fall, amounts in this particular case to about 300 volts, the minimum value for hydrogen gas and a platinum electrode. Across this space of 0.5 cm. or less, the potential drop is as great as across the remaining

13.5 cm. This means that the rate of dissipation of energy in this 0.5 cm. of path is equal to that in the remaining 13.5 cm.; in the present case, 0.176 watt (0.586 m.a. × 300 volts) out of a total of 0.350 watt. This great rate of dissipation of energy in a non-luminous region has an important bearing in luminous efficiency.

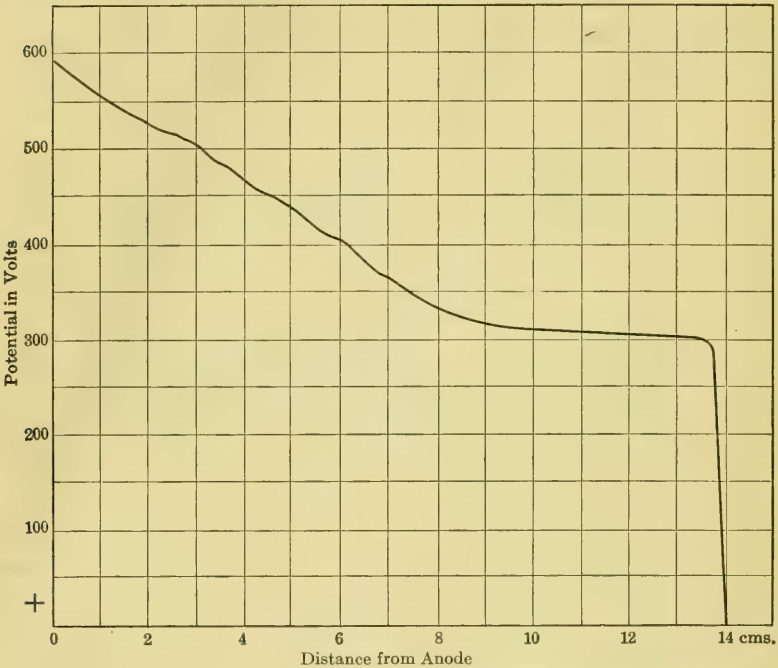


FIG. 40. Variation in Potential with Distance in a Striated Vacuum Discharge, Obtained by Integration from Fig. 38.

Normal and Abnormal Discharge Conditions. — From the standpoint of the cathode fall of potential, vacuum-tube discharges are classified as normal and abnormal. The normal discharge is characterized by a cathode fall which remains constant with change in the discharge current. The potential drop is the minimum value for the given residual gas and cathode material. It is equal to the minimum sparking potential for the given gas and electrode material. Values for various combinations of atmosphere and electrode are given in Table XXVII. These minimum sparking potentials are the smallest differences of potential which under the most favorable conditions of pressure — the maximum pressure accompanying a discharge in which the anode is in contact with the sharp edge of the negative glow — are able to maintain self-sustaining discharges.

TABLE XXVII

Minimum Sparking Potentials for Various Atmospheres and Electrode Materials

Atmosphere	Potentials in Volts for Electrodes of									
	Pt	Hg	Ag	Cu	Fe	Zn	Al	Mg	Na	K
H_2	300	...	295	280	230	213	190	168	185	172
N_2	232	226	...	...	...	...	...	207	178	170
O_2	369	...	...	...	...	...	...	310	...	...
He	160	142	162	177	161	143	141	125	80	69
Air	340	...	...	...	...	...	...	...	...	...
A	167	...	...	...	...	...	100	...	...	...

From the standpoint of low cathode drops, Zn, Al, Mg, Na and K are to be preferred as cathode materials to the other metals named; and the inert gases, He and A, as residual gases to the others named. The above data are important in the designing of low-voltage vacuum-discharge tubes.

The upper limiting value of current for the normal discharge occurs when the cathode glow just covers the cathode (excluding such parts of the cathode as are so close to the walls of the tube or to obstacles as to prevent the formation of the negative glow between them). For smaller currents, the cathode glow covers only a portion of the cathode. The actual area covered is conditioned, in any given instance, on an approximately constant current density. This current density varies with the residual gas, its pressure, and the cathode material. Thus, for a pressure equal to that due to 1 mm. of Hg, the current density in nitrogen at a platinum cathode is 0.33 m.a. per sq. cm.; in nitrogen at an aluminum cathode 0.47 m.a. per sq. cm.; in air at a platinum electrode 0.4 m.a. per sq. cm. From the general relation that current density in the normal discharge varies directly as the pressure, other current densities are obtainable.

The abnormal discharge is characterized by a cathode fall which varies with change in the discharge current. The potential drop is always greater than the minimum sparking potential. The current density in the cathode glow is always greater than that occurring in the normal discharge — its minimum value. In any particular tube, the excess of the cathode drop over that in the normal discharge varies inversely as the pressure and directly as the square root of the excess of the current density over the normal value.

The Conduction Process. — The mechanism of gaseous conduction has been discussed in the section on "Incandescence and Luminescence" (Chapter I). As stated, it consists of the directed movement of positive ions toward the cathode and of negative ions toward the anode. When a negative ion from the discharge is driven against the anode, an electron enters the anode; when a positive ion comes in contact with the cathode, the ion receives an electron from the cathode and becomes a neutral molecule. There results the two-directional transportation in the gaseous atmosphere in conjunction with unidirectional transportation in the metallic circuit without the piling up of electrical charges.

It is possible for ions to become loaded with neutral atoms or molecules and thus become large aggregations. Such loading may occur in vacuum-tube discharges in certain regions; but, for the most part, results indicate that the negative ion is an electron and that the positive ion is a positive residue of an atom or a gaseous molecule minus an electron.

In order that a discharge may be maintained, it is essential that there be some source of ions. These may be provided in several ways: (1) The gas may be ionized by an external agent such as X-rays from some outside source. (2) Electrons may be driven off from the cathode by exposure of it to ultra-violet light of certain frequencies; that is, by the photo-electric production of electrons. (3) The source may be the thermionic emission of electrons from a hot cathode. (4) The discharge, once started, may manufacture its own ions through ionization by impact of the electrically driven ions against neutral molecules.

Self-sustaining discharges are limited to the methods of ion production described under (3) and (4). Method (3) is the case of the arc, which has been considered as a separate main type of light source. Method (4) is the one involved in vacuum-tube discharges used as light sources.

The Relative Ionizing Powers of Positive and Negative Ions. — Ionization by electron impacts has been discussed under "Incandescence and Luminescence." The process that takes place when the impacts are due to positive ions is probably similar. Quantitatively, however, there are great differences. The probable causes are the great differences in mass and size. The mass of an electron is 9.01×10^{-28} gr., its diameter about 4×10^{-13} cm. The mass of the hydrogen molecule, the smallest (except helium) and the lightest of all molecules, is 3.32×10^{-24} gr., its effective diameter about 2.3×10^{-8} cm. The ratio of masses is 1:3700; of diameters, about 1 to 6×10^4.

Now, if ionizing is a mechanical process, it is to be expected that not

only the energy delivered by the impact but also the method of delivery will be important. The mean free path of the positive ion is less than that of the electron. This, combined with the apparent fact that the ion loses at the impact practically the whole of its directed velocity, means that on the average the positive ion does not attain between impacts the kinetic energy that the electron does. The force on the two being the same, the work done between impacts by the field setting them in motion is less for the larger positive ion because the distance is less.

The relatively great difficulty experienced by the positive ions in reaching ionizing velocities and in delivering impacts of an ionizing nature is responsible for the great cathode potential drop in ordinary vacuum discharges. Without that great drop, it seems impossible to obtain, frequently enough for self-maintenance of the discharge, the combinations of ionizing velocities and ionizing types of impact.

The Maintenance of a Self-Sustaining Discharge. — The maintenance of a discharge requires the continuous production of ions. In the self-sustaining discharge, which is independent of any external source of ionization, ions must be formed at the cathode, for if electrons are not formed or liberated there, there will be no means of ionizing in the negative glow and no means provided for the carrying of the discharge current. The cathode will not emit electrons unless it is very hot or unless it is subjected to tremendously high field strengths. Therefore, the method of ion and electron production at the cathode must be one of ionization. Since at the cathode the motions of the electrons are in the wrong directions for them to have attained ionizing velocities, the ionizing that does occur at the cathode must result from the impacts of positive ions.

A large potential drop between cathode and negative glow is favorable for ionization by positive ions leaving the negative glow. These positive ions after ionizing atoms at the cathode together with the positive ions there formed, which escape recombination, at once receive electrons from the cathode and become neutral molecules or atoms. However, those electrons freed by the ionization, which escape immediate recombination, are forced away by the field toward the negative glow. On their way certain impacts take place, resulting in further ionization; but owing to the strong field very little recombination takes place until the region of low potential gradient in the negative glow is reached, where conditions satisfactory for a great amount of ionization and recombination of ions and the consequent glow are found. The mutual dependence of the ionizations in the negative glow and the cathode glow upon each other is nicely shown by the introduc-

tion of an obstacle in the Crooke dark space. The glow in the normal projections from this obstacle upon both the cathode glow and the negative glow disappears.

The relatively low potential gradients between negative glow and anode are due to the fact that the electrons coming from the negative glow are not required to ionize the gas on the way to the anode in order that the discharge current may be carried. That it does ionize the gas in the positive column is an incidental factor which is fortunate from a light-production standpoint.

The Vacuum Discharge as a Source of Light. — What has been said on the production of light following complete or incomplete ionization in the section on "Incandescence and Luminescence" applies directly here. The luminous regions of the discharge are regions in which there are, as a result of ionization, copious supplies of ions for recombination.

Since energy dissipated in the Crooke dark space is not directly productive of light, but rather of maintenance of discharge, luminous efficiency considerations indicate that the energy dissipated there should be reduced as far as possible. There are at least four methods of procedure along this line: (1) selection of a residual gas which is easily ionized; (2) selection of a cathode material which acts very favorably as a catalyst in the production of ions at the cathode; (3) selection of a cathode of sufficient size to permit of a low cathode fall when in operation; and (4) selection of operating conditions with a large proportion of the total potential drop across the tube located in the positive column. Another important consideration from a different viewpoint is (5) the selection of a residual gas whose radiation falls largely within the desired portion of the visible spectrum.

The hopes for a new light source based upon the vacuum discharge will depend primarily upon the finding of a gas or vapor which, when electrically excited in the discharge tube, will yield radiation falling predominantly in the visual region, so as to produce high luminous efficiencies, or, if not predominantly so, in such manner as to produce desired color effects. As to the efficiency, the theoretical limit seems to be approximately that of the maximum visibility of radiation, viz., 670 lumens per watt.

The Mercury-vapor Lamp

Conduction Process. — A graphic picture of the electrical conditions in the arc column of the mercury-vapor lamp would show them to be quite similar in some respects to the conditions of the vacuum-tube discharge, but different in other respects, the tube being filled during

operation with mercury molecules, mercury ions and electrons. These molecules, ions and electrons are moving with various characteristic velocities and in individual directions determined by their collisions with their fellows, according to the kinetic theory of gases. This commotion, characteristic of all gas molecules, is further complicated by the fact that a constant difference of potential of about $1\frac{1}{3}$ volts per inch of arc length is maintained on the electrodes, and that because of the heat of the cathode and the impact of the electrons, ions and molecules on each other and on the electrodes, more electrons and ions are produced than are usually needed to carry the current. The effect of the electromotive force on this gas column is to produce the arc current, which may be considered as a continuous drift of electrons from the cathode to the anode and a relatively much slower movement of positive ions toward the cathode. The excess of ions and electrons produces the effect of a partial short circuit which has a continuous tendency to become more complete. The result is a periodic increase of current and fall of potential of a frequency determined by the capacitative and inductive reactance of the arc column and of the supply circuit.

Color. — The whiteness of the mercury-vapor light is due to the combination of the nearly complementary hues of the yellow-green lines with the blue and violet lines. The difference between such a subjective white and true white light is apparent only when one examines objects of colors other than those making up the subjective white, since, as has been said elsewhere, colored objects have their color by virtue of the colored light they are able to reflect.

On the basis that white light is one-third each of red, green and blue, the mercury arc light gives the effect of being 29 per cent red, 30 per cent green, and 41 per cent blue. Green and red produce the sensation of yellow; therefore, the mercury arc light may be said to be 59 per cent yellow and 41 per cent blue, there being an excess of 1 per cent green and 12 per cent of blue light more than needed to produce the sensation of pure white. This excess of blue and green is apparent. The variation from whiteness in comparison with other commercial illuminants and for sunlight is shown in Table XXVIII.

In connection with modern high-efficiency light sources, a question is sometimes raised as to the amount of ultra-violet light from the various sources and the possible pathological effects. In this connection only the ultra-violet light transmitted by ordinary glasses, as indicated for crown glass in Fig. 41, is to be considered. While this is the region of the maximum sensitivity of ordinary photographic plates as is also indicated in Fig. 41, researches have shown that, regardless

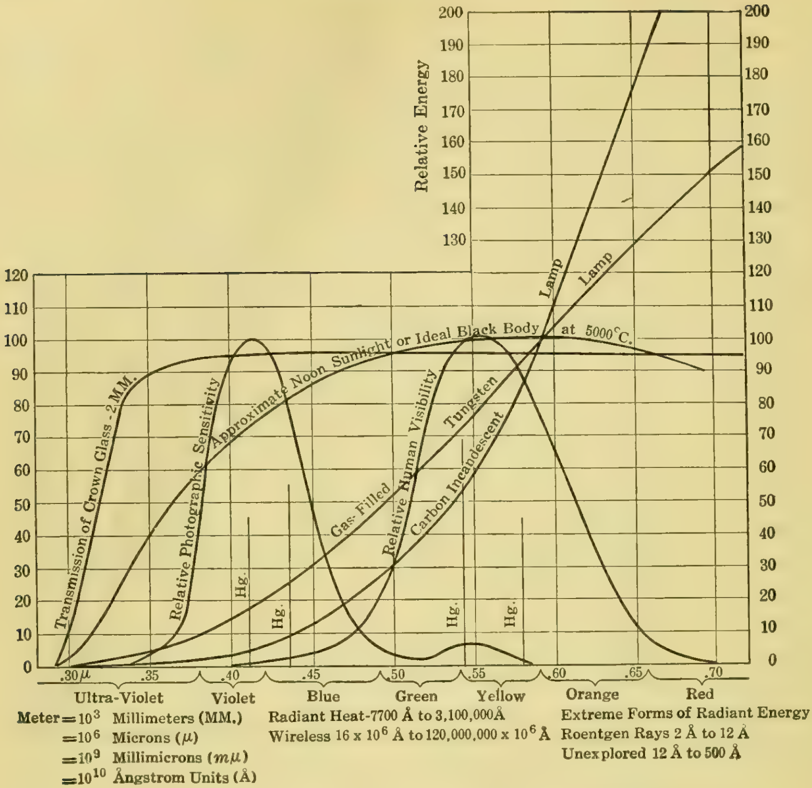


FIG. 41. Energy Distribution in Various Illuminants.

TABLE XXVIII

	Sensation Value		
	Red	Green	Blue
Black body at 5000 (perfect radiator)	33.3%	33.3%	33.3%
Blue sky	26.8	27.2	46.0
Afternoon sun	37.7	37.3	25.0
Carbon (Gem) lamp	50.9	40.6	8.5
D.C. carbon arc	41.0	36.3	22.7
Mercury-vapor arc	29.0	30.3	40.7
Hefner lamp	54.3	39.5	6.2
Carbon incandescent lamp	51.1	40.5	5.4
Acetylene	48.6	40.8	10.6
Tungsten incandescent lamp	48.3	40.8	10.9
Nernst	49.2	40.7	11.1
Incandescent gas mantle, $\frac{1}{4}$% cerium	42.5	40.8	16.7
Incandescent gas mantle, $\frac{3}{4}$% cerium	45.4	42.0	12.6
Incandescent gas mantle, $1\frac{1}{4}$% cerium	47.2	41.8	11.0
Yellow-flame arc	52.0	37.5	10.5
Moore carbon-dioxide tube	31.3	31.0	37.7

of the source, the ultra-violet light transmitted by ordinary glass lamp bulbs or tubes has no appreciable pathological effect on the human eye.

Operation

Starting of a Discharge. — The starting of a discharge in a vacuum-tube consists in the creation of a source of electrons within the tube. This may be brought about by outside ionizing agents by heating the cathode or a part of it to incandescence, or by applying excess voltages to the discharge terminals and thereby giving the few scattered ions always found present (probably in consequence of penetrating radio-active rays) the necessary speeds for producing ions by collisions and establishing ultimately the mutually dependent luminous cathode and negative glows. This latter method is the usual one. It requires temporarily a much higher voltage than the voltage which will maintain a discharge once started.

To start the mercury-vapor lamp, it is only necessary to start and maintain the formation of electrons in a so-called " hot spot " on the surface of the mercury cathode Collisions with mercury molecules immediately result in the formation of more electrons and ions than are needed to form a current, with results to be detailed later. The temperature of this spot may be accounted for by the very small cross-section of the spot and the fact that some 18 watts of energy are converted into heat in this small area of liquid vapor intersurface, the cathode drop in potential being about 5.3 volts. There is a difference of opinion as to whether ionization at the cathode results from the direct emission of electrons from mercury vapor heated far above its boiling point or whether it results from the impact of positive ions upon hot molecules. In either case the condition is easily produced by bringing the mercury cathode into contact with the anode and then breaking the circuit thus formed, as with the ordinary carbon arc. This tilting method is now used to start the relatively small quartz-mercury lamps. An alternative automatic starting method, standard for the glass lamps, consists in short-circuiting a small current through the arc-regulating inductance in series with the arc. This current is broken by a mercury switch or " shifter " magnetically operated by the inductance coil itself. The resulting induced high potential is sufficient to start a localized cathode discharge and the arc is formed. A metallic coating placed on the outside of the cathode end of the tube opposite the mercury cathode and connected to the positive side of the supply circuit, serves to increase the electrostatic capacity of the cathode and hence to give a greater current density to the induced high-potential

discharge when it is localized to form an arc. (See Figs. 42 and 43 for the arrangement of the circuits.)

The heat of the cathode hot spot in an operating lamp is highly

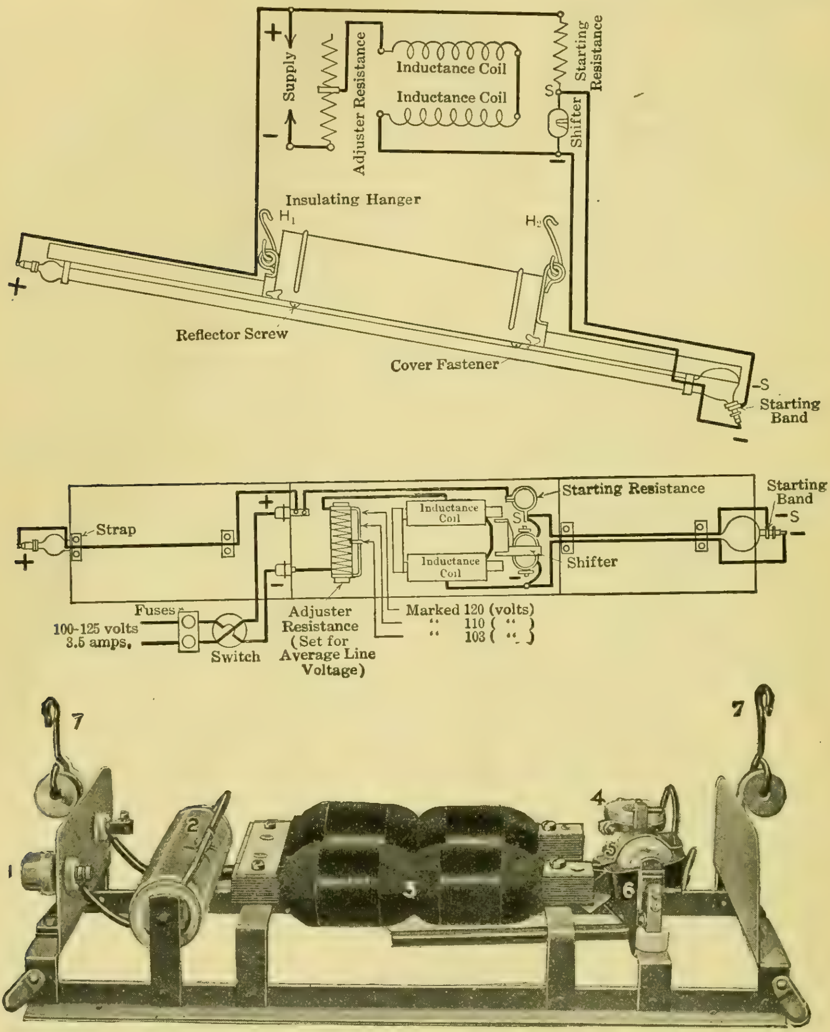


FIG. 42. Arrangement of Circuits for Direct-current Mercury Vapor Lamp and Detail of Auxiliary.

localized, so that in a glass mercury-vapor lamp the arc column temperature varies from some 500° C. in the center to about 125° C. at the surface of the tube. Therefore, the vapor pressure seldom rises above 1 millimeter. There is a potential drop at the anode of about 5.7 volts,

and the anode is so designed that its temperature is normally about 350° C.

When operated upon an alternating current, the filament temperature of an incandescent lamp follows the fluctuation of the current, produc-

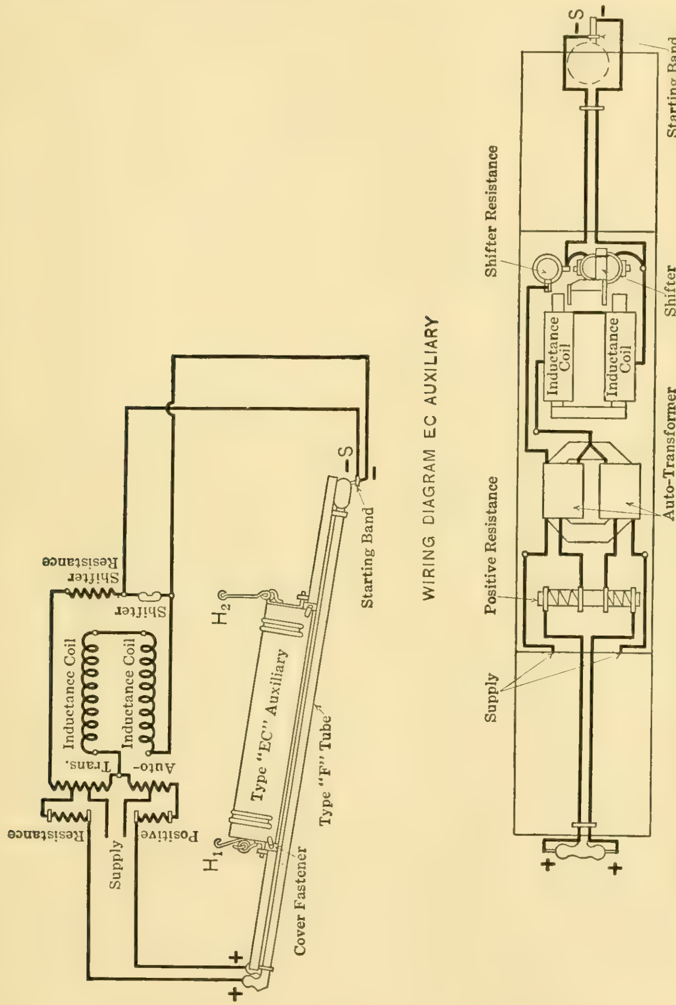


FIG. 43. Arrangement of Circuits for Alternating-current Mercury Vapor Lamp.

ing flicker of twice the current frequency. Because of the persistence of vision, this flicker is only noticeable on low-frequency circuits. The nature of the work largely determines whether this flicker will be objectionable. The multiple images and optical illusions, known as the stroboscopic effect when associated with periodic circular motion, are

most noticeable in connection with moderately high-speed machinery and light sources of high intrinsic brilliancy. In the alternating-current mercury-vapor lamp, the actual tube current is not alternating but a pulsating direct current. Furthermore, the intrinsic brilliancy is very low and the light source correspondingly large. Both of these properties permit the use of this lamp on 25-cycle circuits except under very unusual conditions.

Characteristics

The wattage of a lamp of a given size is limited by the heat-resisting quality of the glass used. Two types of lamps have, therefore, been developed, one of glass to operate at relatively low temperatures, and

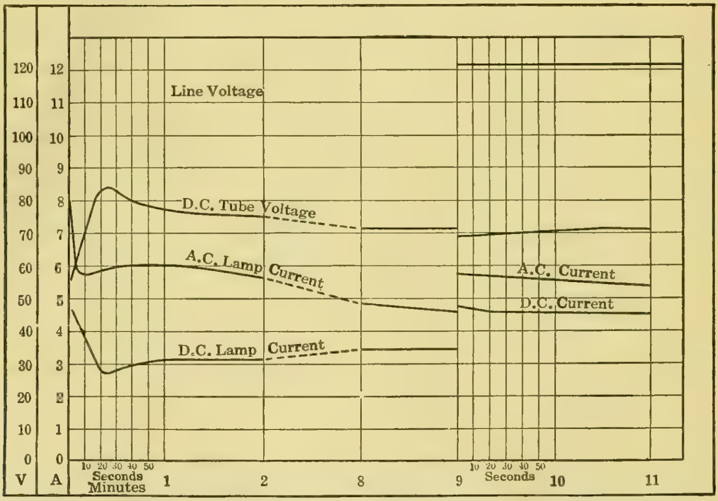


FIG. 44. Volt-ampere Starting Characteristics of Standard Lamps.

one of fused quartz to operate at relatively high temperatures. The normal volt-ampere characteristic of a lamp is determined primarily as a very complex function of the mercury-vapor pressure and density and of the length and cross-section of the tube. With the tube dimensions fixed, the vapor pressure is determined largely by the minimum temperature within the tube, while the vapor density varies according to the heat distribution, being in general a minimum along the central axis of the tube. In standard industrial units, the normal volt-amperage is then finally determined through the tube temperature by a condensing chamber in the form of a bulb on the cathode end of the lamp tube. A condition of complete equilibrium is reached when the light

and heat radiated and conducted from the tube equal the electrical energy input. The effect on the tube characteristics of the temperature rise during starting is shown in Fig. 44, where the voltage and current are plotted as functions of time. In the actual design of a lamp these several variables are so balanced as to give at once that critical vapor density at which the light-giving efficiency is greatest and a volt-ampere characteristic allowing maximum current regulation with a minimum sacrifice of wattage for that purpose.

For transient variations of the current, this inverse variation of voltage is characteristic of the mercury arc, a cathode phenomenon apparently, for the whole range of practical current values and arc temperatures. It is most pronounced for low currents, but decreases rapidly with increase of normal current. For slow changes of the current, this same volt-ampere relationship is characteristic up to a certain critical current value. With further increase of current from this point, the tube voltage passes through a minimum and then rises rapidly as shown in Fig. 45. For maximum light efficiency, the mercury-vapor lamp is operated at the point of minimum tube voltage, where, if unrestricted, the arc current will fluctuate over a wide range on constant voltage. In order to operate this unstable and essentially constant-current device on supposedly constant-voltage power lines, two forms of regulation are necessary. The current is steadied by an inductance coil, connected in series with the arc and as directly as possible to the cathode, so as to oppose every transient action of the current by an instantaneous induced reaction. The falling voltage characteristic of the arc as well as the voltage variations of the line are compensated by

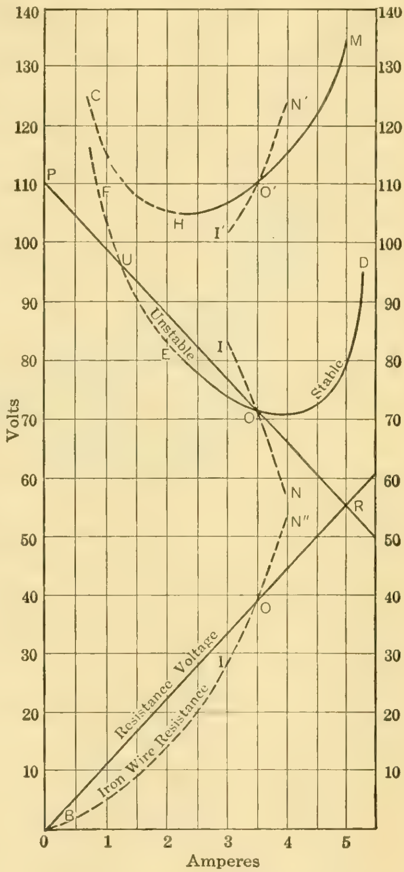


FIG 45. Volt-ampere "Stationary" Characteristics Regulation.

an ohmic resistance in series with the inductance coil and the arc as shown in the wiring diagram, Fig. 42. This resistance is so chosen that, for normal operation, with any increase of current, the decrease in arc voltage will be less than the increase in resistance potential. In Fig. 45, curve *DOEUF* is the volt-ampere characteristic of a mercury arc showing inherent stability above and instability below 4 amperes. Line *PUOR* represents the line voltage minus the resistance voltage for various currents; or, in other words, the voltage available at any time for arc operation. Point *U* is, therefore, one of arc instability, since any current increase is accelerated by the resulting excess arc voltage. On the other hand, point *O* is one of stability, a current decrease being opposed by an excess of arc voltage and an increase being limited by the available arc voltage. In this case, the regulating series resistance is 11 ohms. Curve *CHOM*, the volt-ampere characteristic curve of the whole lighting unit, is the continuous sum of the resistance potentials *BOR* and the arc potentials. Point *H*, therefore, represents the minimum maintenance current and voltage of the outfit for the amount of regulation used.

With continued use, it is found that the pressure due to the residual gases in discharge tubes gradually decreases. This results finally in a condition in which, for both the starting and the maintenance, higher voltages are required. The molecules of the gas are driven upon the electrodes or the glass walls, where they adhere, or even, as tests show, into the glass or electrodes. Some of the gas may be recovered by heating the glass walls of the tube, and the tube thereby may be partially rejuvenated. This phenomenon is quite similar to that which occurs in vacuum tungsten lamps, where residual gases are also driven into the walls of the containing vessel.

The Alternating-current Mercury Arc Lamp

The alternating-current lamp is a highly specialized form of single-phase constant-voltage mercury-vapor rectifier. As shown in Fig. 46 the construction is identical with that of the direct-current lamp except that there are two anode electrodes. The current in the lamp tube is a pulsating direct current of a frequency twice that of the alternating current, as is apparent from the oscillograph curves of Fig. 47. The mercury arc is essentially an unidirectional conductor because it is dependent upon the existence of a so-called cathode " hot spot " which forms on the mercury electrode but not on the iron electrode. This can be formed and maintained at a low voltage, 5.3 volts at ordinary temperatures, only on mercury and certain of its alloys, and once formed

is itself only maintained by continuous operation. The cathode of the lamp is connected through inductance to the middle point of the secondary of an auto-transformer, while the anodes are connected to the terminals. Therefore, the cathode is continuously negative with respect to one or the other anode during operation. The arc is started by an induced voltage, the mercury electrode becoming the cathode for the reasons indicated above. Thereafter, the cathode functions as continuously negative with respect to one or to the other anode. Thus the two halves of the transformer secondary and the anodes connected

FIG. 46. Alternating-current Mercury Vapor Lamp.

to them function alternately, the arc shifting from one to the other anode with the alternations of the supply current. The series inductance, in addition to steadying the current for transient variations, has the more important function of sustaining the cathode spot and the arc current during the time of zero voltage, or, in other words, of causing the current to a given anode during a half cycle to lag its voltage and overlap the current to the other anode to such an extent that the resultant arc current never falls below the minimum maintenance value. Although the potential between the two anodes is obviously double that between the active anode and the cathode, there is little or no leakage between them, since no cathode spot is formed on them under usual conditions. For an alternating current of a given frequency, the minimum sustaining inductance is definitely determined and this also fixes the maximum practical power factor of the outfit.

Regulation, such as that provided by series resistance in the case of the direct-current lamp, could obviously be provided by inductance or choke coils instead of ohmic resistance at a slight gain in efficiency, but with the disadvantage of low power factor, viz., 50 per cent.

Figure 47 shows some of the relations between voltage, current and time in various parts of the standard alternating-current lamp. *A*, the primary voltage, is approximately a sine function as usual, but the current wave form, *B*, is distorted by the reactance and the arc characteristic of the secondary circuit. *D* is the electromotive force between the arc cathode and the active anode, while *H* is the electromotive force during the succeeding half cycle when the other anode becomes the active one. *C* is the anode current corresponding to voltage, *D*, while *G* is the current in the other anode during the succeeding half cycle. *E* is the voltage drop in the anode resistance units during their current-carrying intervals. *I* represents the superimposed anode currents, while *J* is the resulting rectified arc current. *L* shows the superimposed arc voltages and their induced overlap which causes the anode current to overlap as in *I*. Curve *K* showing the voltage drop in the direct-current reactance coils is of unusual interest. The inductive reactance of the arc circuit and the arc characteristics causes the pulsating arc current to rise more slowly than it decreases. The point of anode-current overlap also comes during the time of arc-current decrease. The bearing of these facts upon the wave form of the direct-current reactance voltage is evident from *J* and *K*. Thus points of zero voltage correspond to zero time rate of current change, maxima and minima of current, or to momentarily constant current; while the points of maximum voltage come when the time rate of current change is a maximum. The effect of the overlap discontinuities of the arc current on the corresponding induced voltage maximum is evident. During the period of current overlap, current flows to each anode, and there is during that time no potential difference between them, as shown by a prolonged

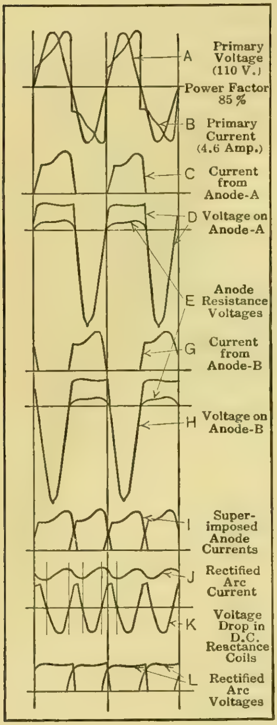


FIG. 47. Oscillograph Record of Alternating-current Lamp Characteristics.

interval of zero voltage on the approximate sine curve of the voltage between the two anodes. The energy represented by this variation from the full sine curve form of the transformer secondary electromotive force is momentarily absorbed in the common coils of the transformer, which are constructed for high self-inductance against each other.

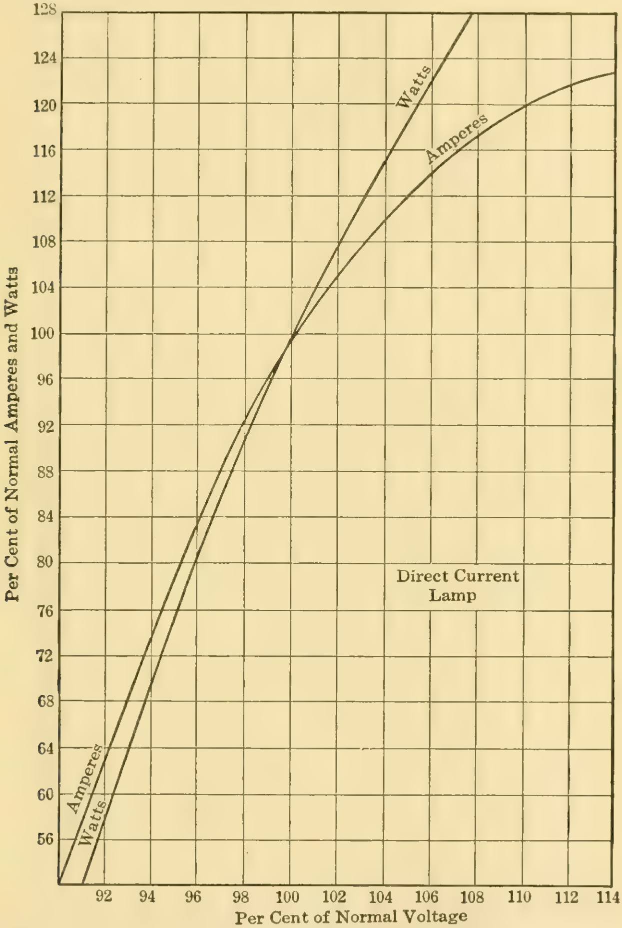


FIG. 48. Current and Power Variations with Varying Voltage for the Direct Current Mercury Arc Lamp.

As is evident from *B* and *J*, Fig. 47, the tube current fluctuates over a much smaller range than does the usual alternating current. This fact and the lower intrinsic brilliancy account for the success of the lamp for high-intensity illumination on alternating current of frequencies as low as 25 cycles. On the other hand, alternating-current lamps

are built for operation on frequencies as high as 133 cycles by modifications in the auto-transformer design.

Constant-voltage power distribution is the rule, but variations from line-voltage ratings due to inadequate power-station equipment, faulty distribution systems, and occasional local overloads, are as universal.

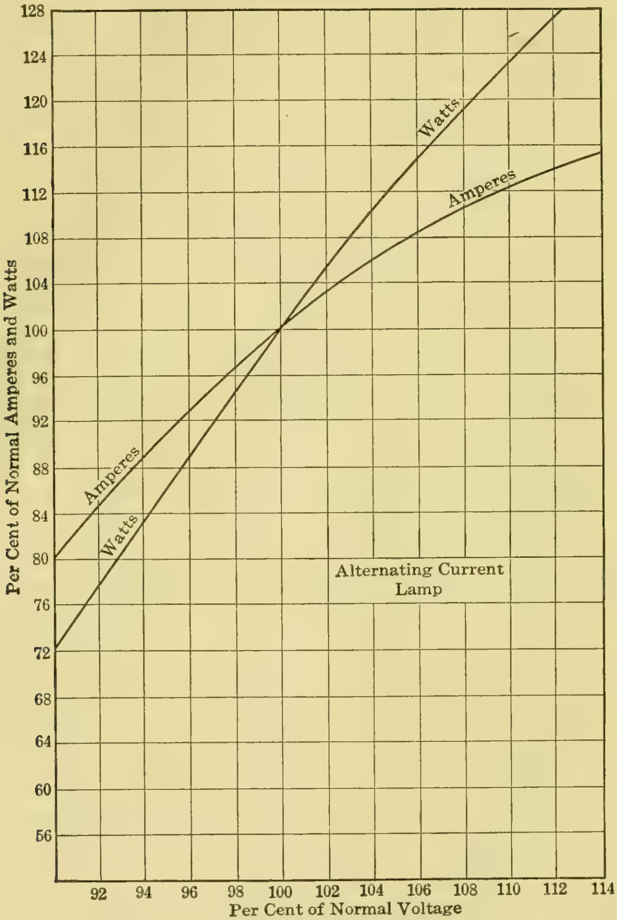


FIG. 49. Current and Power Variations with Varying Voltage for the Alternating Current Mercury Arc Lamp.

Therefore, the current, wattage, candlepower, efficiency and other operating characteristics of most electric lighting units are best studied as functions of the applied voltage and in terms of variation from normal operation.

The variations in current and energy with varying voltage are as

shown in Fig. 48 for the direct-current lamp as regulated for ordinary voltage variations from 110 volts. The lines would be slightly more curved for normal operation on higher voltage, straighter for lower voltage, depending upon the amount of regulating series resistance.

The variations in current and energy with varying voltage are as

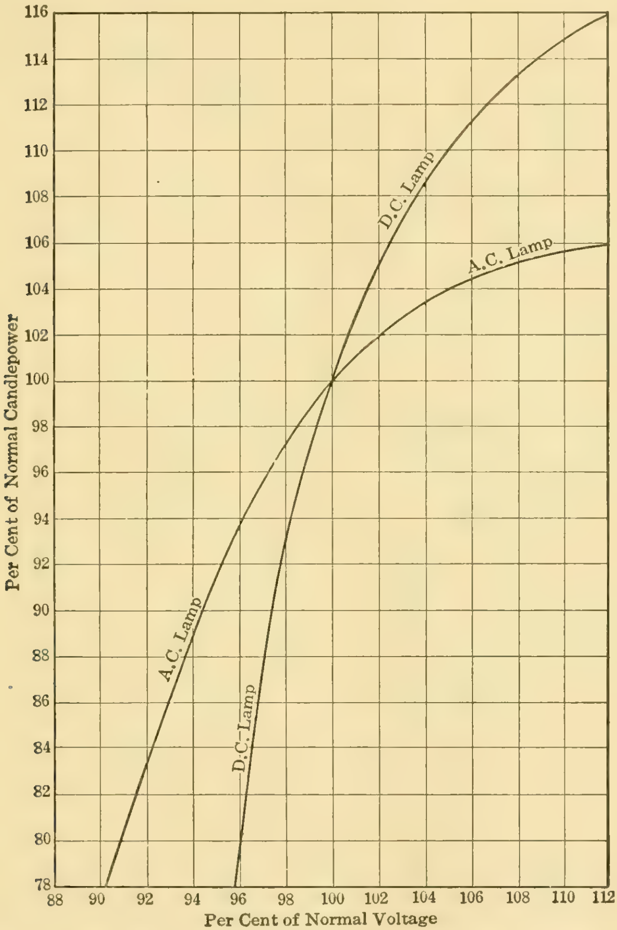


FIG. 50. Candlepower Variation with Varying Voltage for Mercury Vapor Lamps.

shown in Fig. 49 for the alternating-current lamp. In this lamp normal operation at various voltages is provided for by a choice of transformer taps. The regulation of the outfit is, therefore, unchanged, and these curves are general in their application.

A comparison of Figs. 48 and 49 shows that the regulation of the

alternating-current lamp is about two and a half times as great as that of the direct-current lamp. The greater curvatures of Fig. 49 show the effect of the positive temperature coefficient of resistance of the iron wire resistance unit used in the alternating-current auxiliary. As is evident from Figs. 45 and 49, the ohmic resistance of the iron wire

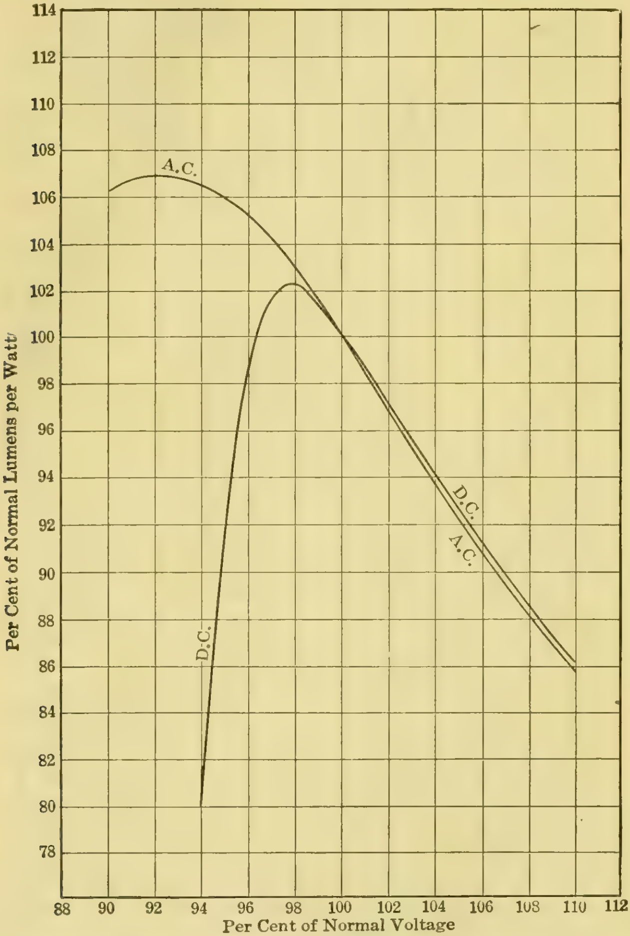


Fig. 51. Efficiency Variation with Varying Voltage for Mercury Vapor Lamps.

increases with increase of current in contrast to the nearly constant resistance of the resistance unit used in the direct-current outfit, and hence the ratio of the current to the voltage, the apparent conductance of the outfit, decreases with an increase of energy input and vice versa. Obviously, too, the regulation is greater when the lamp is operating on

over-voltage since a relatively larger proportion of the energy is being absorbed in the series resistance units.

Figure 50 shows the variations in candlepower with varying voltages. Here, again, the greater regulation on over-voltage, as well as the greater normal regulation of the alternating-current lamp, is apparent. Although of little practical importance, it is of interest to note that, aside from the matter of efficiency, the direct-current lamp operates to the best advantage on over-voltage while the alternating-current lamp has the advantage on under-voltage.

Figure 51 shows the variations in efficiencies, measured in lumens per watt, with varying voltage. The increase of efficiency with sacrifice of regulation in the alternating-current lamp on under-voltage is apparent.

The decrease in efficiency on over-voltage is a limitation placed by the auxiliary regulating devices and not necessarily a characteristic of the mercury arc itself, since approximately one-third of the energy used in the unit does not contribute to the production of light.

The candlepower data of Table XXIX were obtained by direct comparison with calibrated color filters to reduce the color difference on the comparison field. As the common form of mercury-vapor lamp is distinctly a source of finite area, and especially of finite length, the lamp is photometered at such a distance as to reduce this error to less than 1 per cent, while in calculating the mean spherical candlepower, the usual spherical reduction factor is used. The approximate distribution curve of a bare lamp, Fig. 52, is characteristic of any line source.

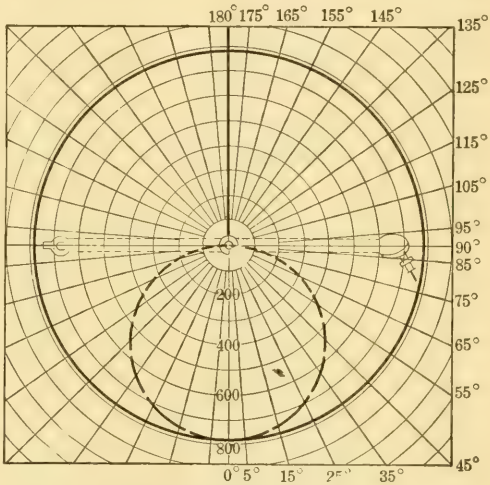


FIG. 52. Candlepower Distribution About a Bare Lamp.

Table XXIX is a tabulation of some of the characteristics of standard types of mercury-vapor lamps. The larger tubes are used in blue-printing machines rather than for lighting, and illumination data are, therefore, omitted. These straight tubes are modified into specialized forms by variations in length and by bending the standard 50-inch tubes into *U* and *M* shapes for photographic enlarging outfits.

TABLE XXIX

Current	Length of luminous tube in inches	Terminal Volts	Amperes	Power Factor	Watts	Mean Spher. Cp. Bare	Lumens per Watt Bare	Universal Reflector M.H. Cp.	Watts per Candle	Lumens per Watt	
Direct.........	50	110	3.5	..	385	550	17.9	850	.45	14.0	Illumination Photography
Direct..........	2–50	220	3.5	..	770	940	15.4	1500	.52	12.2	Illumination Photography
Alternating....	50	110 or 220	3.8	85	430	615	17.9	950	.45	14.0	Illumination Photography
Direct*........	67	110	7	..	770	..	..	..	..	..	Blue Printing
Direct*........	67	110	15	..	1650	..	..	..	..	..	Blue Printing
Direct..........	3	110	4	..	440	..	..	..	..	..	Quartz Arc
Direct..........	6	220	3.5	..	770	..	..	..	..	..	Quartz Arc

* Made also for alternating current. Variations in length and shapes of above lamps provide some 25 standard lamp tubes.

Nernst Lamp

[A. G. Worthing]

During the first decade of the present century, the Nernst filament lamp made considerable headway in the lighting field, but along with its high efficiency it possessed certain unsatisfactory features. With the appearance of metal filament lamps possessing still higher operating efficiencies without the disadvantages, it quickly disappeared from the commercial field. Practically none are in use at the present time outside of the research laboratory. However, the possibility of the future development of a high-efficiency lamp based on the same principle of construction and operation seems to be sufficient to justify some consideration of the lamp as it was made and used.

The Nernst glower, closely related to the incandescent gas mantle, and in fact suggested by it, differs from it principally in the method of heating to incandescence. The solid structure of rare earth oxides of the latter is heated with a gas flame while that of the former is heated electrically.

The filament of the Nernst lamp is a solid electrolyte composed principally of rare earth oxides, such as zirconia, yttria and thoria. It was usually shaped, for ordinary 110-volt service, into short rods about 2 cm. long and about 1 mm. in diameter. Platinum wire, wrapped around the rods near the ends and covered with the filament material, served as current leads. For convenient operation certain accessory

mechanisms were necessary: (1) The glower proper at room temperatures is non-conducting and requires preliminary external heating to make it conducting. This was accomplished in the commercial unit by mounting, near the glower, the heater coil which was automatically cut out of circuit when the current passed through the glower proper. (2) As with all electrolytes, the temperature coefficient of resistance of the Nernst filament is negative. Furthermore, the coefficient is of such great magnitude that any increase in current through a filament is accompanied by a decrease in the potential drop over it. For the operation of Nernst lamps on constant-voltage circuits it is necessary to use series ballast resistances, which, together with the glower, give an increase in potential drop over the whole for an increase in current through it. In the commercial unit, a series ballast containing a small iron wire in hydrogen was made use of.

Among the disadvantages possessed by the unit were (1) the interval of several seconds between the starting of the heater coil and the lighting of the filament; (2) the existence of four fundamental parts to the unit, any accident to any one of which was sufficient to prevent the further operation of the unit; (3) the danger which accompanies the use of any incandescent material, unenclosed, in interiors. Due to the electrolytic destruction of the glower material at the electrodes and the evolution of oxygen, it was found impossible to operate the glower for any length of time in a vacuum. It is probable that the glower might safely have been mounted in a bulb containing oxygen, but this was not done.

The operating efficiency of the Nernst glower is somewhat better than that of the metallized graphite filament lamp, called the gem lamp. In color it is about the same as that of the early vacuum tungsten lamps; its color temperature is about 2400° K. It possesses a very high brightness, of the order of the present lower-wattage gas-filled tungsten lamps. Probably its true temperature is not far from its color temperature.

From the standpoint of light production, certain oxides are very favorably selective in their radiation and some are very refractory and capable of withstanding very high temperatures.

A combination of these two factors in some individual mixtures of oxides or nitrides or some other compounds, obtained after the manner of the Nernst glower, and capable of giving a luminous efficiency much beyond the present incandescent sources, is not beyond the bounds of probability.

The Firefly and Other Photogenic Organisms

[A. G. Worthing]

The Firefly. — Ordinarily the production of light is associated with high temperatures or disruptive electrical discharges; but in living organisms possessing ordinary temperatures there are sources of considerable magnitude. How light production is accomplished without any apparent injury to the organism is a question of great theoretical and practical interest.

There are several kinds of fireflies which differ in habits and in endurance, type and color of flashes and glows. Variously they are described as silvery white, bluish green, greenish yellow, reddish yellow and orange red. The luminous organs are generally located in two segments near the rear of the body on the under side. The purpose of these photogenic activities, it is generally agreed, is one of attraction for the opposite sex. It is also possible that the flashes serve to blind or frighten away enemies, and the tendency of the organisms to flash rapidly when touched would seem to be in accord with this view.

Other Living Photogenic Organisms

The firefly is not unique as a light-giving organism. Among animals there may be mentioned the centipedes of the Geophilidæ family, the glow worm, the noctiluca (that which lights by night), the main source of phosphorescence of the summer seas, the deep-water fish of the Scopelidæ family which with their rows of brightly lighted eye-spots appear like miniature warships on a darkened sea, and the ostracod, *Cypridina hilgendorfi,* a small marine animal found in abundance off the coast of Japan. The last-named organisms are readily obtained at night from fish heads, on which they feed. In indication of their possible importance, one experimenter says, " For the size of the animal, the light-giving substance is relatively enormous and its light-giving power incredibly great. Suffice it to say that one part of luminous gland substance in 1,600,000,000 parts of water will give visible light under proper conditions. In higher concentrations the light is correspondingly stronger, plenty strong enough in fact to be used for illuminating purposes could a sufficient quantity of material be synthesized."

Among plants, there are various fungi, e.g., the *Agaricus melleus* which is responsible for the phosphorescence of rotting wood, and various algæ or primitive seaweeds.

Spectral Energy and Luminosity Distribution. — Spectral energy curves of firefly radiation have been obtained by means of a spectral photographic method. By first holding, for a suitable length of time

(1 to 5 hours), several flashing or glowing fireflies in succession in front of the slit of a spectrograph and allowing their radiation to fall on a photographic plate placed in the focal plane, and then by forming an image of an incandescent carbon lamp filament on the same slit and similarly exposing, spectral photographic action curves, similar to the ones shown in Fig. 4, were obtained. From the ratio of the photographic actions at the same wave-lengths and the known spectral energy distribution of the radiation from the carbon filament, the spectral energy curve (Fig. 53) from the firefly radiation has been computed.

The corresponding spectral luminosity curve (see also Fig. 53), showing how the firefly's radiation from the standpoint of visual effects is distributed with respect to wave-length, was then easily obtained with the aid of the visibility curve. It is interesting to note how nearly the two curves coincide when plotted to tangency at the wave-length of maximum visibility. Careful measurements indicated practically no infra-red or ultra-violet radiations.

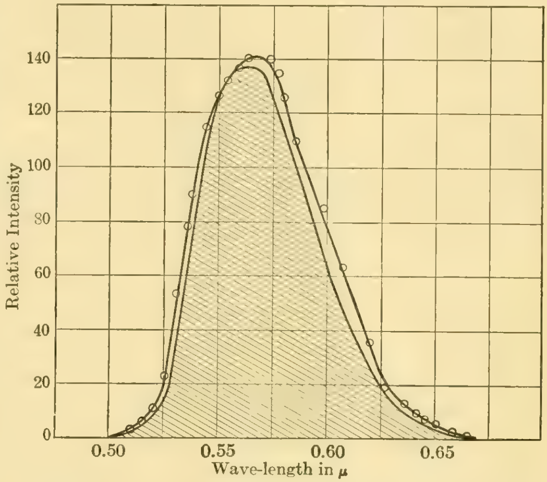


FIG. 53. The Spectral Energy Distribution (un-cross-hatched) and the Spectral Luminosity Distribution (cross-hatched) of the Radiation from a Firefly (*Photinus pyralis*).

The total rate of emission of energy by a glowing Cuban firefly is about 1/100,000 watt; its candlepower is about 1/1600 candle. Other glowing fireflies have candlepowers of 1/250,000 to 1/50,000 candle. During flashing these values may increase ten- or twenty-fold.

Luminous Efficiency. — The efficiency of the *Photinus pyralis* firefly expressed in per cent of the maximum at 0.556μ is given by the ratio of the areas enclosed under the two curves of Fig. 53. It is about 89 per cent. This means in absolute units 560 lumens per watt. Another species, *Photuris Pennsylvanicus*, gives 92 per cent of the maximum or 600 lumens per watt. It is interesting to compare the curves of Fig. 53 with the corresponding curves for tungsten at 2200° K. as shown in Fig. 3 and to contrast these efficiencies with 10 lumens per watt for

vacuum tungsten lamps, 20 lumens per watt for the more efficient gas-filled tungsten lamps and about 35 lumens per watt for the high-efficiency flaming arc.

It should not be forgotten, however, that in the preliminary steps, that is, in the formation of the photogenic compounds, the energy transformations may possibly be attended with considerable waste. Even granting this, there would seem to be great possibilities for conservation of fuel in artificial light production if it were possible to imitate the methods of these photogenic organisms.

Source of Radiation. — The main source of radiation in the firefly and other photogenic organisms is oxidation. In the firefly there are special air passages leading to the luminous organs. Oxygen brought in through these passages reacts with luciferin, one of the two substances secreted within the luminous organs. The second substance secreted is called luciferase. It serves merely as a catalytic agent.

Given the materials, it is not difficult to understand the source of the continuous glow. Flashing, however, involves additional processes, perhaps an intermittent supply of one or more of the materials, or possibly an electrical discharge within the organism. Whatever the process, it seems to be a serious drain on the energy supply of the organism. Repeated flashing, stimulated by the animal's attempt to escape captivity, often results in a short time in death.

Future Possibilities. — The light-emission property of these photogenic organisms is independent of the life of the organism. The active material of fireflies may be dried, reduced to a powder, kept for a considerable time, and later mixed with water containing air in solution, whereupon the luminescent glow will reappear. Likewise, it has been found that the mixing of one of the two secretions found in photogenic organisms with various other organic or inorganic materials, particularly blood, will produce characteristic glows, some bright, some dim. In the *Cypridina hilgendorfi*, as stated, the light production is of such intensity as to be satisfactory for illuminating purposes.

With these facts in mind, and considering the nature of advances in all lines of research in the past, it would seem but a matter of time before the active matter of the secretions of these photogenic organisms will be completely isolated, the substances compounded synthetically in laboratories and supplied in quantity to consumers, who may, either by the admission to the compounded substances of air or oxygen alone, or by its admission in the presence of an electrical discharge, obtain efficiencies which are now only dreamed of. Furthermore, by variations in the active substances corresponding to those occurring with various species of fireflies, or by selection of the containing vessels, the con-

sumer will obtain also, without greatly decreased efficiencies, the æsthetic color effects which all look forward to but cannot, from a practical point of view, always obtain.

PROBLEMS ON LIGHT SOURCES

1. The intensity of the sun's radiation outside the earth's atmosphere, on a surface normal to the rays, is given as approximately 2 calories per sq. cm. per minute. Plot curves showing: (*a*) the rate at which energy is received per sq. cm. of earth's surface as a function of the time of day; (*b*) the amount of energy already received during the day as a function of the time of day. Assume a twelve-hour day in which the sun at noon is directly overhead.

2. Express with the aid of Table VII the lamp efficiencies of the candle, the kerosene, the coal-gas and the acetylene flame in lumens per watt. Compare with 10 lumens per watt for the vacuum tungsten lamp, 20 for the high-wattage gas-filled tungsten, and 40 for certain of the flame arcs. Make a comparison also, taking into account the efficiency of transformation into electrical energy, of energy liberated as heat by burning gas or coal.

COLLATERAL READING

Light Sources

The Black Body

Hyde, E. P., The Physical Production of Light, J. Frank. Inst., **169**, 439 (1910); **170**, 26 (1910).

Pyrometry (American Institute of Mining and Metallurgical Engineers, New York, 1920).

Hyde, E. P., Forsythe, W. E., and Cady, F. E., The Brightness of a Black Body, Phys. Rev., N. S. **13**, 45 (1919).

Mendenhall, C. E., and Saunders, F. A., The Radiation of a Black Body, Astrophys. J., **23**, 25 (1901).

Coblentz, W. W., and Emerson, W. B., Luminous Radiation from a Black Body, Bur. Standards, Sci. Paper No. 305 (1917).

The Sun

Abbot, C. G., The Sun (D. Appleton & Co., New York, 1911).

Abbot, C. G., and Fowle, F. E., Annals of Astrophysical Observatory of the Smithsonian Institution, **11** (Government Printing Office, Washington, 1908).

Encyclopaedia Britannica, **26**, 85 and 88.

Bigelow, F. A., Treatise on the Sun's Radiation (John Wiley & Sons, Inc., New York, 1918).

Gas

Lectures on Illuminating Engineering (Johns Hopkins Press, Baltimore, 1911).

Illuminating Engineering Practice, 1916, I. E. S.-U. P. (McGraw-Hill Book Co., Inc., New York, 1917).

Dibden, W. J., Public Lighting by Gas and Electricity (Sanitary Publishing Co., Ltd., London, 1902).

Gerhard, W. P., American Practice of Gas Lighting (McGraw-Hill Book Co., New York, 1908).

Story of Modern Gas Light, Gas Record, **39**, 71 (1917).

Ives, H. E., Kingsbury, E. F., and Karrer, E., A Physical Study of the Welsbach Mantle, J. Frank. Inst., **186**, 585 (1918).

Bohm, C. R., The Manufacture of Mantles for Incandescent Gas Lighting, J. Gas Lighting, **121**, 33 (1913).

Arc

Keilly, W. E., History of the Electrical Industry.

Ayrton, (Mrs.) Hertha, The Electric Arc ("The Electrician" Printing & Publishing Co., Ltd., London, 1902).

Child, Clement D., Electric Arcs (D. Van Nostrand & Co., New York, 1913).

Thomson, J. J., Conduction of Electricity through Gases (Cambridge, 1903).

Marks, L. B., Flaming Carbon Arc Lamps, N. E. L. A. **1**, 64–85, 252–254 (1909).

Mitchell, A. J., Regenerative Flame Lamp, N. E. L. A. **1**, 204–15 (1909).

Allen, N. A., Illum. Eng., **14**, 19 (1921).

Darrah, W. A., Trans. Am. Electrochem. Soc., **29**, 613 (1916).

Electrician, **31**, 502 (1893); **38**, 615 (1897).

Roosa, G. W., Long-Burning Flame Carbon Arc Lamps, Elec. J. (June, 1913).

Karrer, E., Efficiency of Flame Arcs, J. Frank. Inst., **183**, 61 (1917).

Mott, W. R., The Characteristics and Uses of the Flaming Arc, J. Cleveland Eng. Soc. (March, 1917).

Mott, W. R., The Colors and Light Production of Different Elements in the Arc in Relation to Arc Images, Trans. Am. Electrochem. Soc., **31**, 365 (1917).

Trotter, A. P., Proc. Royal Soc. (London), **56**, 262 (1894).

Trotter, A. P., Elec., **29**, 11 (1892).

Trans. Am. Electrochem. Soc., **37**, 665 (1920).

Incandescent Lamps

Barham, G. B., The Development of the Incandescent Electric Lamp (Scott, Greenwood & Son, London, 1912).

Hutchinson, R. W., Jr., High-Efficiency Electrical Illuminants and Illumination (John Wiley & Sons, New York, 1911).

Solomon, M., Electric Lamps (D. Van Nostrand, New York, 1908).

Percival, G. A., The Electric Lamp Industry (Sir Isaac Putnam & Sons, London, 1920).

Harrison, W., Electric Lighting (Chicago, 1920).

Bulletin of the Bureau of Standards, **11**, 483 (1915); **12**, 589, 607 (1915) (Government Printing Office, Washington).

Nela Research Laboratories: Abstract Bulletin No. 1 (Jan., 1913); No. 2 (Jan., 1917); No. 3 (Oct., 1922).

Schroeder, H., History of Incandescent Electric Lamp Manufacture, Gen. Elec. Rev., **14**, 426 (1911).

Paterson, C. C., The Evolution of the Electric Lamp, Elec., **77**, 822 (1916).

Scott, R., Evolution of the Lamp, Trans. I. E. S., **9**, 138 (1914).

Howell, J. M., Incandescent Lamp, Trans. A. I. E. E., **18**, 923 (1901).

Yearly Reports of Lamp Committee, Proc. N. E. L. A., 1908 to date.

Yearly Reports of Committee on Progress of the Illuminating Engineering Society, Trans. I. E. S., 1914 to date.

Merrill, G. S., Incandescent Lamp Developments, Trans. I. E. S., **11**, 525 (1916).

Vapor-Tube Lamps

Ives, H. E., White Light from the Mercury Arc and its Complementary, Bur. Standards Bull. **6**, 265 (1909–10).

Jones, L. A., Hodgson, M. B., and Huse, K., Relative Photographic and Visual Efficiencies of Illuminants, Trans. I. E. S., **10**, 963 (1915).

Mees, C. E. K., Artificial Illuminants for Use in Practical Photography, Trans. I. E. S., **10**, 947 (1915).

Pole, J. C., Photometry of Mercury-Vapor Lamps, Trans. I. E. S., **6**, 306 (1911).

Bell, Louis, On the Ultra-Violet Energy in Artificial Light Sources, Elec. World, **59**, 807 (1912).

Buttolph, L. J., The Cooper Hewitt Mercury Vapor Lamp, Gen. Elec. Rev., **23**, 741, 858, 909 (1920).

Firefly

Harvey, E. Newton, The Nature of Animal Light (J. B. Lippincott Co., Philadelphia, 1920).

CHAPTER III

PHOTOMETRY

[F. E. Cady]

Definition. — Photometry is that branch of illuminating engineering which deals with the measurement of light. It may be said to be the background without which the science and art of the subject would be an impossibility. The measurement of the result produced by light sources in rooms, halls, stores, factories, on the streets, and, in general, indoors and out-of-doors, has led to the development of methods of lighting and their application, and, where satisfactory results have been obtained, has permitted descriptions which in turn enable the results to be duplicated.

Importance. — The importance of photometry has been recognized to such an extent that there are departments devoted to that subject in the great standardizing bureaus of Germany, France, England and the United States. It was due to the efforts of the Department of Photometry of the Bureau of Standards that standard specifications for the purchase of incandescent lamps were agreed upon and are now used in the purchase of millions of lamps. The gas interests abroad organized, as far back as 1900, an International Photometric Commission to deal with problems relating to photometry. Subsequently, this Commission was reorganized to include electric lighting interests.

Applications. — Photometry is used to determine the reflecting power of surfaces, such as painted walls, and the distributing power of shades placed around lamps. In former days, photometry was used almost exclusively to determine the light-giving power of sources, but it is now used in the measurement of the illumination produced by these sources, and also in the solution of experimental problems in physics and other sciences; in the study of the densities of photographic plates; and in optical pyrometry to measure high temperatures. In other words, the field of application of photometry has broadened enormously and is still growing.

The Eye. — Photometry deals with the measurement of the ability or the capacity of light to affect the eye. It is not concerned with the velocity of light or the pressure of light or its action on plants or chemicals, except in so far as photometric principles or apparatus are used in

conjunction with the study of these characteristics. In all photometric measurements, the eye is, then, the final arbiter. It is the fundamental photometric instrument. However, the eye is extremely insensitive when it comes to making a direct judgment of the difference between the light-giving power of two sources. Fortunately, the eye is very sensitive to slight differences in brightness of two contiguous illuminated surfaces, and, with suitable devices, very small differences can be detected. This enables a zero method to be employed and is responsible for the development of the subject. When it comes to the question of measuring lights differing in color, a complication is introduced, due to the fact that, roughly speaking, the eye is not equally affected by the different colors of the spectrum. Numerous efforts have been made to find suitable apparatus and methods to replace the eye, but the results obtained by the so-called "physical" photometers must always be standardized in terms of those obtained with the eye.

Definitions. — The following discussion is based on the work of the Committee on Nomenclature and Standards of the United States Illuminating Engineering Society.[1] In photometry, the word "light" is used in two different ways; either to designate the visual sensation produced normally on the eye by radiant flux; or to denote the luminous flux (q.v.) which produces the sensation. There are four fundamental subjects or concepts associated with light; i.e., luminous flux, luminous intensity or candlepower, illumination and brightness. Of these, luminous flux is taken as the basic concept, and candlepower, brightness, and illumination are defined in terms of it.

Luminous Flux

The use of the word "flux" as applied to light is of comparatively recent origin. "Luminous flux" was probably first suggested by Professor Blondel of Paris in 1894, and was given a definition by the International Congress of Electricians at Geneva, Switzerland, in 1896. The Illuminating Engineering Society of this country has been advocating its adoption for some years and now most lamp manufacturers give their lamps a rating in lumens (the lumen is the unit of flux) instead of in candlepower.

The definition given at Paris in 1920 by the International Commission on Illumination is as follows: **"Luminous flux (F) is the rate of flow of radiant energy evaluated with reference to visual sensation."** Someone has suggested as an hydraulic analogue the case of a hollow ball studded with small holes and connected to a supply of water under pressure. The water would then stream out in all directions permitted

[1] This Committee will be referred to as the I. E. S. Committee.

by the holes. In the same way, electrical energy is transformed in a lamp filament to radiant energy which streams out in all directions, and that which is visible to the eye is called luminous flux. One of the principal advantages of this concept is the fact that it facilitates comparison of various sources on the basis of their light output or production, per unit of power input, and further makes possible a consideration of light in space wholly apart from the source producing it or any surface on which it might impinge.

Luminous flux is defined as a *rate* of flow of radiation (properly evaluated) and is analogous to power, which is a *rate* of doing work. But it is common practice to speak of power as transmitted and as coming from a source such as a motor, and, in a similar way, luminous flux is spoken of as being emitted, transmitted, or intercepted. In recognition of this use, the International Commission added the following note to the definition of luminous flux: **"Although luminous flux must strictly be defined as above, it may be regarded for practical photometric needs as an entity, since the rate of flow may for such purposes be considered constant."**

Candlepower

If, in the case of any given source, the flux in all directions were equally distributed, it would not be necessary to introduce the term candlepower or luminous intensity. But there is no practical source where the distribution of flux in all directions is the same, and hence the need of some term, such as luminous intensity or candlepower, to indicate the solid angular density of the flux in a given direction. Thus, consider a luminous source, s, of small dimensions and a small solid angle having its origin at the source and its axis in a direction P (Fig. 54 A) and including a uniform flux distribution. Suppose the solid angle to be 0.01 of a steradian and the flux to be 0.1 lumen. Then the solid angular flux density, or flux per unit solid angle, would be $0.1 \div 0.01$ or 10 candles in the direction P. A similar solid angle in a different direction might include 0.5 lumens and the flux density would then be 50 candles.

If the light source is partially surrounded by a surface which absorbs all the radiation falling on it and reflects none of it as light, the candlepower in a direction through the opening is unchanged (Fig. 54 B and C). Thus the candlepower in one direction does not tell much about the flux, but the average candlepower is a very important factor in flux measurement.

Candlepower then involves direction, and for a particular source shows its capacity for producing luminous flux in the given direction.

While it is common practice to speak of the candlepower of a source, what is meant is the candlepower in a specific direction or the average in a number of directions.

Definition. — The definition given in the 1918 Report of the I. E. S. Committee is as follows: **" Luminous intensity, *I*, of a source of light in a given direction is the solid angular density of the luminous flux emitted by the source in the direction considered when the flux in-**

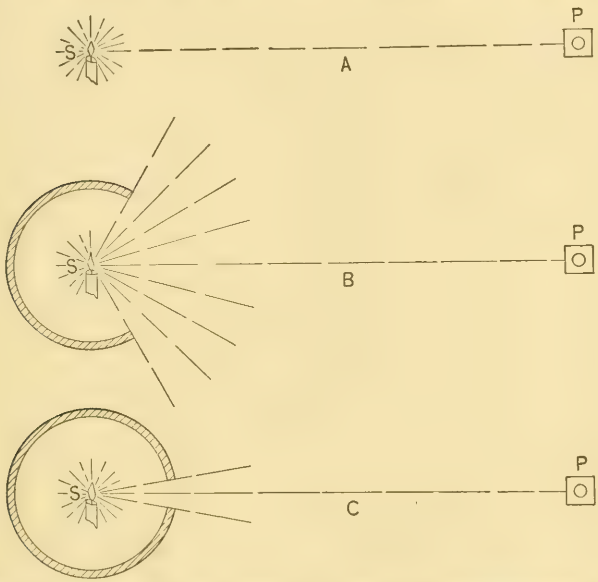


FIG. 54. The Candlepower in the Direction of the Photometer is Not Changed by Partially Surrounding the Light Source with a Non-reflecting Surface.

volved acts as far as computation and measurements are concerned as if it came from a point; or it is the flux per unit solid angle from that source in the direction considered. $I = \frac{dF}{d\omega}$."

Mean Horizontal Candlepower. — Photometry deals with candlepower from three standpoints: the intensity in a single direction from the source; the average intensity in a horizontal plane normal to the axis of a source (generally a rotating source), called the mean horizontal candlepower; and the average intensity in all directions, called the mean spherical candlepower.

NOTE. — Inasmuch as the word "intensity" is used so frequently to indicate extent or quantity of other things, the term "candlepower" will, in general, be used throughout this book to indicate luminous intensity, and it is hoped thereby to avoid confusion.

The candlepower in a single direction is used in the case of stationary or non-rotating sources, such as flames, and in the case of incandescent lamps when they are to be used in a stationary position. In the latter case, the direction in which the candlepower is measured is sometimes indicated by marks on the bulb. In the case of cylindrical or conical flames, the candlepower in all directions in a plane normal to the axis of the flame is generally the same. When the candlepower of an incandescent lamp is spoken of, it is the mean horizontal candlepower which is referred to, unless otherwise defined.

Mean Spherical Candlepower. — The mean spherical candlepower is the average of the luminous intensities in all directions throughout a sphere having the source at the center. Or, considering a source having a uniform intensity in all directions, it is the candlepower which such a source would have to have in order to produce the same flux as the source in question. The mean spherical candlepower can be determined if the total flux is known, by dividing the latter by 4π.

Unit of Candlepower. — **The unit of luminous intensity is the candle, and the term candlepower is the luminous intensity expressed in candles.** While flux, as was previously stated, is taken as the fundamental photometric quantity and luminous intensity is derived, the fundamental *unit* is that of luminous intensity, the candle, and from a measurement of candlepower, values of flux and illumination are derived by computation.

The adoption of the term "candle" as the name of the unit of luminous intensity was perfectly natural, since at the time it was adopted, candles were the most reliable sources available as regards constancy and reproducibility. Considering the uncertainties in a unit maintained by standard candles, the American Institute of Electrical Engineers in 1897 recommended that the unit be based on the hefner lamp, and in 1902 recommended that the value assigned to the unit should be $\frac{1}{0.88}$ of the hefner. This value was generally accepted for a number of years.

International Candle. — As the result of work done at the Bureau of Standards in 1904 and 1905, Hyde recommended that the unit be kept through the agency of incandescent lamps. He also inaugurated a movement which, with the assistance of the American Institute of Electrical Engineers, the American Gas Institute, and the Illuminating Engineering Society, was successfully brought to a conclusion whereby England and France agreed to join this country in adopting a common value for the unit, which has since been called the "international candle." The unit in use at that time in this country was reduced

by 1.6 per cent and thus brought into agreement with the existing units in France and England. Germany has so far refused to accept the unit, but has agreed to coöperate from time to time in comparisons to determine the relation between the international candle and the hefner At the present time 1 international candle $= \frac{1}{0.9}$ hefners.

Unit of Luminous Flux

Lumen. — The lumen is the unit of luminous flux and is equal to the flux emitted in a unit solid angle by a source whose average candlepower throughout the unit solid angle is one candle (Fig. 55). A source having a uniform luminous intensity of one candle in all directions would emit 4π lumens. The total luminous flux from a source whose candlepower in all directions is not uniform is computed from the mean spherical candlepower by multiplying by 4π, for if the source

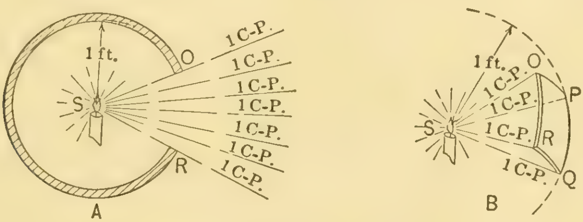


Fig. 55.

A — Opening OR has an area of 1 square foot and emits 1 lumen.
B — One lumen falls on surface OPQR.

is considered at the center of a sphere of unit radius, the total surface of the sphere will intercept all the flux and this total area is 4π. This was formerly the common method of getting the total flux, but the introduction of the integrating sphere has made feasible the use of standards rated in lumens.

It may be well to emphasize the importance of candlepower and its relation to luminous flux. Until the introduction of the present high-powered, gas-filled tungsten incandescent lamps, practically all photometric measurements of lamps involved a determination of luminous intensity in candles. City specifications for gas street lighting called for gas of a certain candlepower. Incandescent lamps purchased on specifications were required to have a certain mean horizontal candlepower. In the calibration of standards and instruments, the candlepower was and still is the principal factor and the quantity most frequently measured in experimental work. The total flux in lumens of a

standard incandescent lamp is determined by obtaining the mean spherical candlepower, either directly or through measuring the mean horizontal, or the mean zonular candlepower, and multiplying this mean spherical candlepower by 4π. The growing popularity of the flux rating for incandescent lamps is pushing the general use of the idea of candlepower more and more into the realm of experiment and science.

Candlepower is then always associated with a source, whether self-luminous or otherwise, and gives information regarding the luminous flux at its origin.

Illumination

After the flux has left the source, it may be used directly to attract attention as in the case of signal lights or some sign lighting; but in the great majority of cases, it is produced in order that it may be made to impinge on a surface, to produce what is called *illumination*, and the measurement of illumination comprises the major part of the photometric work to be done by the illuminating engineer.

Definition. — Illumination is connected with the *flux received* or *intercepted* by a surface, and unless designated as uniform, or as average, it refers to the incident flux at a particular point on the surface. **Illumination at a given point of a surface is the luminous flux density on the surface at the point, or the incident flux per unit of intercepting area.** The symbol used is E and the equation is $E = \frac{dF}{dS}$, where the illumination is not uniform. If the dimensons of the source of the flux are small relative to the distance considered and if r is the distance from the source to the surface and the latter is normal to the flux direction, $dF = I\,d\omega$ and $dS = r^2\,d\omega$; $\therefore E = \frac{I}{r^2}$. If the normal to the surface makes an angle θ with the direction of the flux, or, in other words, if the flux is incident at an angle θ, $E = \frac{I\cos\theta}{r^2}$. Note that, if the illumination is not uniform, it is not proper to speak of the illumination on a surface without either having it understood that the average illumination is referred to, or specifying the location of an infinitesimal area which has the stated illumination. It should be emphasized that illumination is always *flux* per unit area, not candles per unit area.

Lux and Foot-candle. — The International Commission on Illumination defined the " lux " as the practical unit of illumination and equal to 1 lumen per square meter, but the earliest unit and the one still most

widely used is the foot-candle. **One foot-candle is the illumination, produced at a point on a surface, which at the point is normal to the direction in which a source, located at a distance of one foot, has an intensity of one candle.** One foot-candle is 1 lumen per square foot. Using the centimeter as the unit of length, the unit of illumination is 1 lumen per square centimeter, called a phot. An effort is being made to give illumination values in lux or milliphots, but up to the present time it will be found that practically all values given in the technical literature are in foot-candles.

Various Units. — The various units of illumination may at first seem confusing, but if it is remembered that, within certain limits to be discussed later, illumination may be derived from the value of the candlepower by dividing by the square of the distance between the source and the surface, i.e., $E = \frac{I}{r^2}$, then it will not be difficult to distinguish the units and pass from one to another. If the distance is measured in feet, the illumination will be given in foot-candles; if in meters, in lux or meter-candles; if in centimeters, in phots. 1 foot-candle = 1.076 milliphots. (1 sq. m. = 10.76 sq. ft.) To put it another way, a lamp which has a luminous intensity of one candle in a direction normal to a surface will produce, if the surface is one foot distant, an illumination of one foot-candle; if the surface is one meter distant, an illumination of one lux; if the surface is one centimeter distant, an illumination of one phot. It should be self-evident that the phot represents an illumination many times as great as the foot-candle. If it is desired to use for illumination the expression " flux per unit area," then to avoid confusion the word " incident " should be put before the word " flux." If this is done, there will be no danger of having it mistaken for the expression " flux per unit area " when this expression means " brightness." In the latter case, it should be written " emitted flux per unit area."

Determination of Flux. — In order to determine values of flux from candlepower and illumination, it should be remembered that either the distribution or the average value of each must be known, for the former in the solid angle and for the latter over the given surface. Thus, to determine the flux coming out in a certain solid angle from a flood-lighting unit, the size of the angle and the average candlepower must be known; or, considering as useful flux that which reaches the side of a building to be lighted, its magnitude may be computed if the average illumination and the area of the building surface are determined.

Water Analogy. — Another water analogy compares the flux to the capacity of a pond and the candlepower in a single direction to the depth

of water below one point in the surface of the pond. Measurement of this depth would not tell much about the capacity of the pond. The average of a series of measurements at points along a medial line would give more of an idea and would be analogous to the measurement of the mean horizontal candlepower. But the capacity of the pond would be quite accurately determined by measuring the depth at a large number of points taking the average and multiplying by the area. In a similar way, the flux may be determined, as previously stated, by finding the average candlepower in all directions (the mean spherical candlepower) and multiplying by 4π (the area of a unit sphere).

Photometric Laws

Inverse Square Law. — The inverse square law states that if a surface is intercepting normally luminous flux emanating from a point, the illumination at any point of the surface will vary inversely as the square of the distance between the two points. This law may be illustrated as follows: Assume the source to be the center of a series of concentric hollow spheres of radius 1, 2, 3, 4, etc., and consider the flux from the source contained in a given solid angle ω. The bounding surface of this solid angle cuts the various spherical surfaces enclosing areas which are proportional to the squares of the radii, 1, 2, 3, 4, etc., since by definition the solid angle is the quotient of the area of the intercepted surface divided by the square of the radius. But the flux included in this solid angle remains constant, and since it is spread over areas successively larger in proportion to the square of the radii, the illumination or flux per unit area must be successively less in the same proportion.

Limitations. — The law as stated holds rigorously only for a source which has infinitely small dimensions, where the intervening medium has negligible absorption, and the surroundings of both the source and the surface are perfectly black. But in practice, errors due to the last two causes can usually be neglected, and, excepting such sources as searchlights and those involving reflectors, any source whose dimensions are negligibly small, compared to the distance at which it is measured, can be treated as if its flux were coming from a point. Consider for instance an incandescent lamp filament and a point A in that filament. A flux of light is coming from that point in every direction. If there is placed at B, a distance which is considerable with respect to the height of the filament, a photometer screen, it will subtend at A a small solid angle, $d\omega$, and the flux, dF, in that angle divided by the angle, or $\frac{dF}{d\omega}$, will be the luminous intensity in the direction AB due to this point.

But every other point on the filament is also sending flux to B and the sum of all the intensities is the candlepower of the filament in that direction, and it is found in measuring it that the same value for the candlepower is obtained as would be obtained if all the flux were coming from a single point located at the correct distance from B; so that while the actual candlepower of all sources is due to a great many points, it can be shown by computation and has been found by experiment that for all sources except those of a certain type, if the measurement is made at a sufficient distance, the candlepower can be determined as if in the given direction all the light from the source were concentrated at a point.

Errors. — Since all known light sources have finite dimensions and since this law is involved in the great majority of photometric measurements, it is important to know what errors are introduced when it is used. It can be shown mathematically that if the light source is in the

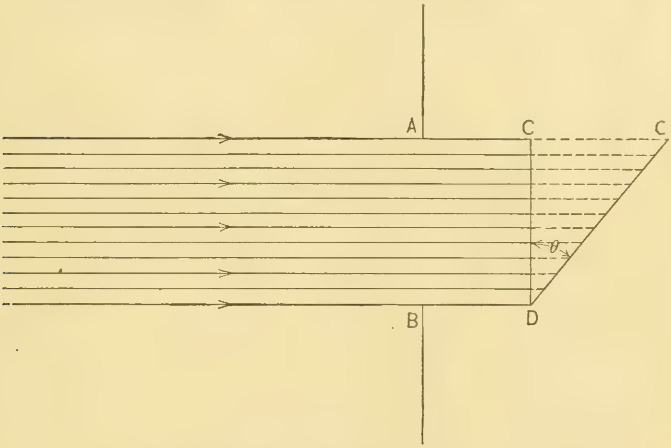


FIG. 56. Illustrating Lambert's Cosine Law of Incidence.

form of a straight line or cylinder, the distance error introduced in computing the illumination by using the inverse square law will be negligible if the distance of the photometer screen from the source is more than ten times the length of the line or cylinder. In the case of a flat, circular disk, the distance should be more than twenty times the diameter if the error is to be less than 0.2 per cent.

Cosine Law — Incidence. — Lambert studied the illumination received by a surface due to flux incident at various angles and enunciated the law that **the illumination on a surface varies directly as the cosine of the angle between the incident ray and the normal to the surface.** Thus, if light is passing through a screen, AB, Fig. 56, and strikes a surface, CD, normal to the direction AC, CD will have a certain average

illumination measured by the flux divided by the area. If now the surface CD be rotated about D as an axis through an angle θ, then the area $C'D$, intercepted by the flux, will be larger, or equal to $\frac{CD}{\cos\theta}$. Hence, the flux is spread over a larger area, and, therefore, the illumination or flux per unit area is less, or $E = F \div \frac{CD}{\cos\theta}$ which is equal to $\frac{F\cos\theta}{CD}$. This is ordinarily called Lambert's cosine law of incidence.

Emission. — Lambert also studied the light flux from a diffusing surface and stated the law that **the intensity of the light emanating in a given direction from a perfectly diffusing surface is proportional to the cosine of the angle of emission measured between the normal to the surface and the emitted ray.** This is known as Lambert's cosine law of emission. The only source at present known which obeys this law rigorously is the theoretical radiator, the black body.

Talbot's Law. — Another law, used more particularly in the photometric measurements of candlepower, is known as Talbot's law. If a beam of light is intercepted by a rapidly rotating disk from which sectors have been cut, the appearance of a surface illuminated by the beam will be the same as it would be if illuminated by a beam whose intensity was the same fractional part of the original beam as the angular opening in the disk is of 360 degrees. Thus, if the disk has a series of sector openings whose sum is 90 degrees, it will cut down the intensity of the beam to one-fourth. This law depends on what is known as the "persistence of vision" of the eye, a phenomenon which has made possible the use of moving pictures.

Fechner's Law. — Finally, under the heading of laws might be mentioned Fechner's law which, when reduced to its simplest form, states that differences in sensation vary as the logarithm of the ratio of the stimuli producing the different sensations. If the strength of a sensation were directly proportional to the excitation, a light, A, which is twice as strong as another light, B, would produce a sensation, $A = 2B$, and the mind would in general be able to form fairly accurate judgments of the relative intensities of lights. But, as a matter of fact, the relation between the sensation produced by A and that produced by B is a logarithmic one.

Brightness

The fourth fundamental concept used in photometry is brightness. When light strikes a surface, part of it is reflected, part absorbed, part transmitted. It is by reason of light emitted, transmitted, or reflected

that an object appears bright, and difference in brightness or contrast is one of the most important effects used by the eye to distinguish and identify objects. Thus, in reading ordinary print, it is the difference in brightness of the paper blackened by the ink and the adjoining white untouched portions that enables the letters to be identified. In walking, differences in brightness are frequently a cause of protection from stumbling. In analyzing the lighting conditions in a room, brightness measurements are important because it is differences in brightness which the eye perceives, although they are in general produced by differences in illumination. Again, the photometers most commonly used in practice have as their basic principle the ability of the eye to distinguish small differences in the brightness of contiguous surfaces.

Definition. — In the 1922 Report of the I. E. S. Committee, brightness is defined as **"the luminous intensity per unit of projected area."** The great difference in magnitude between the brightness of self-luminous sources and those luminous by reason of reflected or transmitted light is taken care of in the definitions of the units as given in the following paragraphs.

Candle per Square Centimeter. — **The c.g.s. unit of brightness is one candle per square centimeter of projected area.** In the English system, the unit is one candle per square inch.

A surface of unit brightness emits one lumen per steradian per unit of projected area.

Lambert. — The "lambert" is a practical unit of brightness. It is equal to a brightness of $1/\pi$ candles per square centimeter of projected area. It is the average brightness of a surface emitting or reflecting one lumen per square centimeter, or the uniform brightness of a perfectly diffusing surface emitting or reflecting one lumen per square centimeter.

For most purposes, the millilambert, 0.001 lambert, is the preferable practical unit.

The equation for brightness is

$$b_\theta = \frac{dI_\theta}{ds \cos \theta}$$

where b_θ is the brightness in the direction θ degrees from the normal to the area ds and dI_θ is the candlepower in that direction.

The great majority of surfaces are bright by reason of light reflected; and for such cases, i.e., walls, ceilings, and other surfaces seen by reflected light, brightness is expressed in terms of the flux proceeding from a unit area of the surface, on the assumption that the surface is a

perfect diffuser, i.e., obeys the cosine law of emission or reflection. If the surface does not obey this law, its brightness is said to be the same as that which a perfectly diffusing surface would have if reflecting the same number of lumens per square centimeter. In this case, the formula for computing the brightness is $b_\theta = \frac{dF}{ds} = \rho\, dE$, where F is the emitted flux, ρ is the reflection coefficient, and perfect diffusion is assumed. The result will be expressed in lamberts if E is given in phots. Thus the brightness of the walls in a suburban residence under daylight has been stated to vary from 0.038 millilamberts to 43 millilamberts, and a white wall illuminated to 3 foot-candles might have a brightness of 2 millilamberts, the exact value depending upon the reflection factor. The millilambert is a convenient unit because of its close approximation to the brightness of a perfectly diffusing surface having a reflection factor of unity and illuminated to an intensity of one foot-candle.

Lamberts from Candles per Square Centimeter. — The factor π must be introduced into the computations if an instrument calibrated in candles per square centimeter is to be used for measuring brightness in lamberts. This may be shown by considering one side of an infinitesimal surface, obeying Lambert's cosine law of emission, and having a brightness of b candles per square centimeter. Its brightness in lamberts will be the total flux emitted from that side divided by the area.

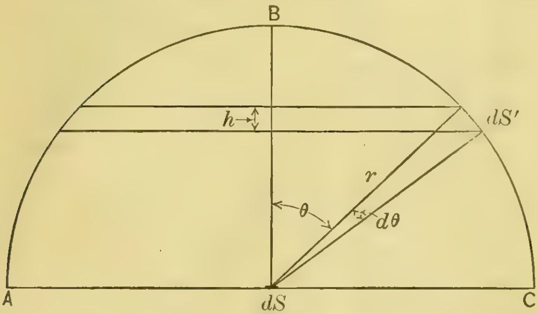


FIG. 57. Computation of Lamberts from Candles per Square Centimeter.

To determine the total flux consider the element dS as at the center of a hemisphere ABC of radius r (see Fig. 57). Let dS' be an element on the inner surface of the sphere, the normal to dS' making an angle θ with the normal to dS. The candlepower I_θ of dS in the direction of dS' will be $b_{I_\theta}\, dS \cos\theta$, since by definition $b_{I_\theta} = \frac{I_\theta}{dS \cos\theta}$. Hence, the illumination at dS' will be $\frac{b\, dS \cos\theta}{r^2}$ since b is the same in all directions for a perfectly diffusing surface. If dS' be rotated about $B\, dS$ as an axis, a zone will be generated whose area is $2\,\pi r h$ where h is taken as the altitude of the zone. But $h = dS' \sin\theta = \sin\theta\; r\, d\theta$.

Hence, the area of the zone is $2\pi r^2 \sin\theta\, d\theta$. The flux intercepting this zone will be the product of the area and the illumination or

$$dF = \frac{2\pi r^2 \sin\theta\, d\theta\, b\, dS \cos\theta}{r^2} = 2\pi b\, dS \sin\theta \cos\theta\, d\theta \cdot$$

The total flux will then be $2\pi b\, dS \int_0^{+\frac{\pi}{2}} \sin\theta\cos\theta\, d\theta = 2\pi b\, dS \left[\frac{\sin^2\theta}{2}\right]_0^{+\frac{\pi}{2}}$ $= \pi b\, dS$. The flux brightness will then be by definition $\frac{\pi b\, dS}{dS}$ or πb. If the brightness of a perfectly diffusing surface has been measured in candles per square centimeter, its brightness in lamberts will be π times the value in candles per square centimeter.

Illustrations. — To illustrate brightness, consider a piece of white blotting paper, whose reflection factor is 0.8, illuminated by a light source which has a candlepower of 10 in the direction normal to the paper. It is known that a good grade of such paper obeys Lambert's cosine law of emission in all directions within an angle of 45 degrees to the normal to within a negligible error. If the lamp is at a distance of 100 cm., the illumination at the paper will be 0.001 phots, or 1 milliphot. Assuming this to be uniform over an area of 1 sq. cm., the incident flux would be one millilumen. Of this, 0.8 is reflected and the brightness would then be 0.8 millilambert. But the incident flux was assumed to be in one direction, and on striking the surface would scatter so that the emitted flux in any one direction would be very much less. If a small area of the paper were blocked off and the candlepower measured in the direction referred to, it would be found that the candlepower divided by the projected area would not be 0.0008 c. per sq. cm. but $\frac{0.0008}{\pi}$ c. per sq. cm.

Diffusion. — In thinking of brightness and expressing it in terms of lamberts, it should be emphasized that since no surfaces encountered in practice obey Lambert's cosine law, their brightness if given in lamberts means that they have the appearance which a perfectly diffusing surface would have if made to have the same brightness in lamberts. While it is true that a perfectly diffusing surface appears equally bright at all angles of view, since such surfaces are not found in practice, the angle of observation should always be stated when expressing the brightness of either a reflecting surface or a self-luminous source.

Distance. — It should be further noted that brightness, like candlepower, is independent of the distance between the object and the observer to within the ordinarily negligible error due to absorption by the intervening atmosphere. If one recedes from a street lamp, for

instance, it looks equally bright as long as it is visible. The reason lies in the fact that while the light flux entering the eye diminishes in proportion to the square of the distance, the solid angle subtended by the lamp, and hence the image of the latter, diminishes in the same ratio and the brightness of the image remains constant. Again, just as the specific gravity of a substance does not depend on any specific amount of it, so brightness does not depend upon the extent of the bright surface. The filament in a 40-watt tungsten lamp is much longer and bigger than the filament in a 10-watt lamp, yet both may have the same brightness. The area in the one case is very much greater than in the other, but the candlepower is greater by exactly the same amount and hence the ratio is the same. In the case of surfaces which reflect specularly, such as polished metals, glass and mirrors, the departure from Lambert's cosine law of emisson is so great that the usual ideas of brightness do not apply. In such cases, what is ordinarily of interest is not the brightness of the surface, but that of the virtual or real images seen by reflection from the surface. The brightness of the images will obviously depend upon the character of the reflecting surface.

Curves

In addition to the general quantities already defined, a number of others referred to in the Report of the I. E. S. Committee should be mentioned. Thus, in testing the quality of the output of lamp manufacturers, both in the case of gas mantles, arc and incandescent lamps, photometric work is carried on and data obtained from which are plotted certain curves. A performance curve is a curve showing the behavior of a lamp in regard to its candlepower, watt consumption, or other characteristics at different periods during its life. A characteristic curve is a plot showing the relation between two variable properties of a source; for example, how the candlepower of a gas mantle varies with the gas pressure. This should not be confused with the distribution curve as used in illumination data.

A distribution curve is a plot of the candlepower measured at various angles, generally in one plane, horizontal or vertical. Certain conventions have been recommended by the Illuminating Engineering Society in this connection. Thus, the vertical distribution curve is defined as a polar curve representing the luminous intensity of a lamp or lighting unit in a plane passing through the axis of the unit and having the unit at the origin. Unless otherwise specified, a vertical distribution curve is assumed.

Reduction Factor. — The spherical reduction factor of a lamp is defined as the ratio of the mean spherical candlepower to the mean

horizontal. For a source whose luminous intensity is uniform in all directions, this factor would be unity. For a straight cylindrical filament obeying Lambert's cosine law, it is $\pi/4$.

Photometric Axis. — The photometric axis is an imaginary line parallel to the direction of motion of the photometer carriage and generally perpendicular to and passing through the center of the photometric disk, if that is of the flat type.

Standards

Unit and Standard. — It may be well to emphasize the difference between a *unit* and a *standard*. The former is a quantity in terms of which the latter is evaluated. A unit is essentially an idea or concept. A standard is a material object by means of which the idea or unit is utilized. The watt is a unit of electric power. But there is no piece of apparatus called a "standard watt" as there is a standard cell for voltage and a standard ohm for resistance. For each of the three quantities there is a unit, but only for the latter two, individual standards to evaluate it. In the case of light there are several standards in use.

Standards may be divided into three classes: **primary, representative** or **secondary** and **working.**

Primary Standard. — A primary standard is one that can be reproduced from specifications. If all the existing standards were destroyed, the unit could be re-established if a primary standard were known. This, with the exception of the color, is its only absolutely necessary qualification. It must have a constant value for a period only long enough to make a measurement. It need not be simple and it may be expensive to make and expensive and difficult to operate, for, as in the case of the standard ohm, its production, maintenance and operation may be confined to national standardizing laboratories and it may be used only at rare intervals. The Violle platinum standard is an illustration of an effort to produce a satisfactory primary standard.

Representative Standard. — A representative or secondary standard is one that has for its principal requirement constancy for a considerable period after calibration. It need not necessarily be reproducible from specifications, but it should be portable, simple and inexpensive. The incandescent lamp may be cited as an illustration.

Working Standard. — A working standard has for its essential characteristic adaptability for the work in hand. It should be constant enough not to require too frequent calibration, inexpensive and easily procured. An incandescent lamp will serve in incandescent lamp

photometry, but some kind of flame standard should be used in the photometry of gas.

Color. — There is one quality which all standards must possess in common and that is a suitable color. This point has become particularly prominent within the last few years, owing to the difficulty of obtaining, from existing secondary standards, working standards which would match in color the new illuminants such as the gas-filled tungsten lamp.

Primary Standards. — That there are today four primary standards in actual use is sufficient evidence that no one of them has been found sufficiently superior to the others to warrant its general adoption. A primary standard is good if it is reproducible and bad if it is not. Its fitness as a primary standard depends on the accuracy with which it can be reproduced.

Flame Standards. — A flame is the seat of chemical reactions, delicately balanced and subject to sudden and marked variations, and is also the focus of streams of cooling and diluting gases from the surrounding air.

Pressure. — The effect of increasing the pressure in the atmosphere about a non-luminous flame is to make it luminous. Decreasing the pressure around a luminous flame tends to make it non-luminous. Therefore, if a candle is carried up to the top of a mountain, it will tend to burn with a flame like that of an alcohol lamp. The effect of non-combustible constituents of the atmosphere, such as water vapor and carbon dioxide, is in general to lower the luminosity of flames.

Flame Height. — There is a critical flame height which may be taken as normal for a given illuminant. A flame increasing toward the normal height grows hotter, and the decomposition of the combustible is more active. When the normal height is exceeded, the incomplete supply of oxygen produces rapid lengthening of the flame. For practically all flames, the illuminating power varies proportionally with the flame height for limits of at least 5 per cent on either side of the normal height. The effect of pressure is probably also due to the ease with which atmospheric oxygen can penetrate the flame.

Candle

The first primary standard was a candle. Its use in this connection has become insignificant. But for situations where electricity is not available and other standards are inconvenient by reason of their bulk, the candle is used. Its advantages are its simplicity, cheapness and convenience. Its objectionable features are its lack of uniformity, its unsteadiness and variations in candlepower due to wick conditions.

Carcel

The Carcel lamp was employed as a primary standard for many years in France. This lamp burns colza, or rape-seed oil, which is fed to the wick by a small pump operated by clockwork. The difficulty of defining and obtaining a definite purity in the composition of this combustible, combined with other objections, has relegated the Carcel lamp to the position of a secondary standard and its use is very much restricted.

The Hefner

The primary standard invented in 1884 by Herr von Hefner-Alteneck and known as the Hefner lamp (Fig. 58) is the officially adopted standard in Germany, and the intensity of a carefully specified lamp is taken as the unit of light in that country despite all efforts to displace it with the international unit. This lamp has been the subject of numerous tests, and it is generally accepted that the value of the light intensity can be relied upon under specified standard working conditions to plus or minus 2 per cent.

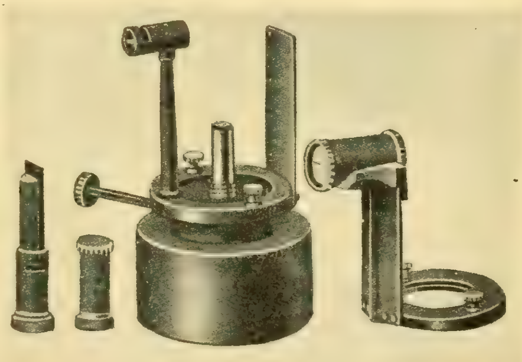


Fig. 58. Hefner Lamp.

Combustible. — The lamp burns amyl acetate, or banana oil, which can be defined and obtained in a state of sufficient purity to meet the requirement of uniformity in the composition of the combustible.

Lamp Parts. — The essential parts of the lamp are the reservoir, the wick-movement mechanism, the wick, the wick tube, and the flame-height measurer. The material used is brass, with the exception of the wick tube which is made of German silver in order to save it from the corroding effect of the amyl acetate. For a similar reason, the interior surface of the reservoir has to be heavily plated.

The material of which the wick is made can be anything suitable as long as it does not fill the tube too tightly or catch in the teeth of the notched wheels used to raise it. The wick is merely a conductor, in

this case, to bring the fuel up to the hot part of the tube. In operation, the top of the wick is from 1 to 3 millimeters below the top of the tube.

Specifications. — The specifications prescribed by the German Physikalische Technische Reichsanstalt cover the dimensions of all the parts and the tests for purity of the amyl acetate. As the lamp is not used as a primary standard in this country, these details will not be given here. It is sufficient, perhaps, to say that the prescribed height of the flame, to give an intensity of one hefner candle, is 40 mm., and a difference of 1 mm. in flame height means from 2.5 to 3 per cent difference in candlepower. Corrections for atmospheric pressure and humidity have to be made when accurate work is to be done, the latest formula reported being as follows:

Corrections. — Candlepower $(I) = 1 - 0.0055\,(x - 8.8) - 0.0072\,(x' - 0.75) + 0.00011\,(b - 760)$, where I = hefner candles; x = humidity expressed in liters of water vapor per cu. m. of dry air free from CO_2; x' = liters of CO_2 per cu. m. of dry air; and b = the barometric pressure in mm. of mercury. In well-ventilated rooms, the CO_2 correction is generally negligible, but the humidity and pressure must be measured and allowed for in all accurate work. 1 hefner = 0.9 international candle.

Advantages. — The advantages of the hefner lamp lie in its reproducibility, simplicity of construction and operation, ease of manipulation, portability, durability, and, with proper fuel and handling, agreement of one lamp with another.

Objections. — Its principal defects are its color, which is more reddish than that of the sperm candle, and the difficulty of setting the flame height exactly right. These two defects are fundamental in any consideration of the hefner lamp as either a primary or a working standard. A third objection is the low candlepower.

International Candle. — The Bureau of Standards has experimented with the hefner with a view to seeing whether it can be improved and continue to serve as a primary standard. They have found that if the flame height is made 45 mm. instead of 40 mm., the lamp will give one international candle. They have also decided that the specifications are not rigid enough with respect to the wick tube, fuel, etc. But it would seem that the color is an insurmountable obstacle.

The Pentane Lamp

The pentane lamp seems to offer more promise, although it is questionable whether any kind of flame standard will ever prove desirable as a permanent primary standard, since there are so many variables to

be looked out for. However, until a better standard presents itself, the pentane lamp is to be preferred to the hefner.

A 1-candle pentane lamp was devised by A. G. Vernon Harcourt in 1877, in which a mixture of air and the vapor of pentane was consumed at a given rate. Later a lamp was devised in which liquid pentane was burned with a wick, but in 1898 the modern form, a return to the first idea, in a 10-candle size, was brought out.

Combustible and Mechanism. — The fuel used is pentane, C_5H_{12}. No wick is used, and the liquid is contained in an elevated reservoir or saturator. Air enters the inlet and mixes with the vapor of pentane as it passes over the liquid, and the mixture flows by gravity down the supply pipe to the burner. The latter is of the Argand type, made of steatite, and has thirty holes drilled in it. Air, heated by passing through the annular space between the inner and outer chimney, flows down through the hollow standard and into the central chamber below the burner. Thus the flame resulting from the combustion of the pentane is fed internally with preheated air coming up through the center of the burner, and externally with the colder outside air. The flame passes up into an inside chimney in which there is a mica window through which the tip of the flame is seen. The height of the flame is regulated by controlling the rate at which the fuel is supplied. The latter is regulated by a stop-cock. The part of the flame used is that between the top of the burner and the chimney. A cylindrical block of wood serves as a gage to set the chimney at the given distance from the burner. This distance should be 47 mm., and when the flame is right the candlepower is a maximum.

Flame Height. — The intensity depends, as with the hefner, upon the *dimensions* of the lamp, the *composition* of the *fuel*, the *atmosphere* in which it is burned, and the *manipulation* of the lamp, especially as regards flame height and the screening of the flame. This lamp differs from the hefner, however, in that a change of 1 mm. in flame height alters the intensity by only about 0.4 per cent instead of 2 or 3 per cent. This makes it possible to screen the flame and utilize only its central zone. The intensity is, of course, a function of the size of the flame itself and this is affected by the dimension of the burner.

Corrections. — The effect of humidity and barometric pressure is similar to that in the hefner. Early values of the humidity factor gave it as higher than for the hefner, but work at the Bureau of Standards indicates that the factor is about the same. The equation, neglecting the effects of CO_2, is

$$I = I_n\,(1 - 0.00567\,(x - 8) + 0.0006\,(b - 760))$$

where I_n is the normal candlepower, whose value is in the neighborhood of 10, and x and b have the same meaning as before.

Advantages. — The advantages of the pentane lamp as compared with the hefner lie in its better color, its higher candlepower, its steadier flame, the small effect of height changes, and its greater present reproducibility.

Objections. — Its disadvantages lie in its bulkiness, complicated construction, and lack of portability, its higher first cost and cost of operation, and the fact that it requires a larger photometer room and better ventilation.

Improvements. — As a result of extended investigations, the Bureau of Standards recommends various modifications in the specifications and design of the lamp, if it is to be used as a primary standard. The idea is to control the fuel and air supply more completely, using electric heating to vaporize the pentane and set up the draft in the burner. Work has been done on the development of a lamp embodying this idea and it is hoped that one will be perfected which will afford a valuable check on the unit of light as at present maintained by incandescent lamps.

Center of Radiation. — Before leaving the pentane lamp, reference should be made to the point in the flame from which the distance to the photometer screen is measured. Theoretical considerations indicate that this point lies midway between the axis and the outer tube, but it has been the practice in all laboratories to measure distances to the flame axis, and thus uniformity of intensity is obtained. In using the lamp, from fifteen to thirty minutes are allowed to elapse after lighting before measurements are begun.

The two standards just described are the nearest approach to a primary standard generally accepted at the present time. But neither of them can as yet be reproduced from specifications with the accuracy with which the unit can be maintained by means of incandescent lamps. Furthermore, since in each case the light is the result of the specified fuel burning in a specified lamp surrounded by a specified atmosphere, the standard is not merely the lamp but the combination of lamp, fuel, and atmosphere, and the last two elements are constantly changing. These changes affect the light as a flame standard and make the errors of measurement many times greater than those made on carbon filament lamps.

Violle Platinum Standard

Turning from flames to electric sources as primary standards, as early as 1881, Violle proposed that the unit of light be that emitted normally by one square centimeter of the surface of molten platinum

at the temperature of solidification. Some essential conditions for the reproduction of this standard are as follows: the platinum must be chemically pure; the mass must be not less than 500 grams; the crucible must be made of pure lime.

Mechanism. — The platinum is melted by an oxy-hydrogen blowpipe and the surface is viewed in a mirror placed above it and at an angle of 45° to the normal to the surface. The difficulties of manipulation have been found so great that this can hardly be considered a satisfactory standard. The value assigned to this standard has been 2 carcels or approximately 20 candles. A modification of the Violle standard was suggested by Lummer and Kurlbaum, and another modification by Petavel.

Arc Lamp

Another suggestion for a primary standard was made by Swinburne and S. P. Thompson, who recommended that portion of the light from the crater of a direct-current carbon arc lamp which would pass through a hole of one square millimeter in an opaque screen. A careful investigation, however, showed that the surface of the crater is constantly changing in brightness.

Incandescent Lamp

Incandescent filament lamps, both of carbon and other materials, have been proposed as primary standards. But no one has as yet constructed suitable examples from specifications and it is only recently that specifications have been given for a tungsten primary standard. The manufacture of vacuum tungsten lamps has become so standardized within the last year or two that the possibility that a tungsten lamp may meet all the requirements of a primary standard is by no means remote.

Helium

In connection with electric primary standards, reference should be made to a standard proposed by Nutting, consisting of a discharge tube filled with helium gas. The pinkish color, low intensity, and lack of reproducibility were its chief defects.

Black Body

Reference should also be made to the suggestion made by a number of investigators that the light from a black body be used as a means of maintaining the unit. Using a properly constructed hollow sphere

or long, cylindrical tube, the candlepower of a definite area, with the radiator at a definite temperature, has been determined experimentally by a number of investigators and found to agree quite closely with theoretical values obtained by computation.

Radiation

An entirely different viewpoint has been presented by Houston, Féry, Ives and others, who propose as a primary standard a definite quantity of radiation from a source, such radiation to be evaluated according to its capacity to produce the sensation of light by being passed through a proper kind of filter.

Reference and Working Standards

There are no reference standards for gas. For a working standard in gas photometry, a calibrated pentane lamp is probably the most reliable of flame standards. In defining a working standard, it was mentioned that flame standards should be used in the measurements of flames. Pentane and other flame standards are therefore used in gaslight photometry, and experience has shown that atmospheric conditions affect the standard and the source to be tested very closely, if not exactly alike. The use of flame standards obviates the necessity of separate determinations of the humidity and barometric correction factors for each source.

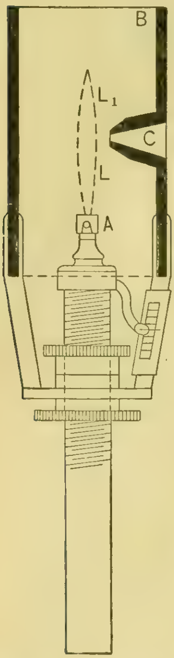


FIG. 59. Vertical Section through Standard Acetylene Burner.

Kerosene Lamp. — Numerous attempts have been made to utilize kerosene in a standard lamp. At present there is in use, as a working standard for gas, a lamp which was brought out in 1906 by A. H. Elliott and seems to be very satisfactory. It is of the student-lamp form, and uses a flat cotton wick and a glass chimney. A metal screen limits the area of the flame used. The lamp gives approximately 5 candlepower and, as tested at the Bureau of Standards, maintained its value constant throughout the day to within 1 per cent. Its advantages lie in its steadiness, cheapness, simplicity of operation, and in the fact that it is very little affected by drafts. Another working standard used in gas testing is the Edgerton standard, which uses coal or water gas as a fuel. It consists of an Argand burner surmounted by a glass chimney around which is a blackened metal sleeve. This sleeve has a slot in the front through

which passes the light to be used, while in the back it is cut away to avoid reflections. It is similar in idea to the Methven screen, but differs in some particulars.

Acetylene. — While acetylene has not yet been found satisfactory for use as a primary standard, an acetylene lamp has been used to advantage in cases where it is inconvenient or too expensive to employ incandescent lamps. A Bray air-mixing type of burner tip, *A* (Fig. 59), is used and mounted inside a cylindrical hood, *B*, with a rectangular opening, *C*, in one side. From this opening, metal leaves extend inward to within about 2 mm. of the flame. The edges of these leaves form an aperture through which a short section of the flame is viewed. The color of the light is very close to that of an ordinary vacuum tungsten lamp.

Incandescent Lamps

Reference Standards. — Properly constructed and seasoned incandescent lamps are the most constant and reliable reference or secondary standards at present available and, for testing incandescent or arc lamps, are also the best working standards. Changes go on in these lamps while they are burning, but such changes are so slow in developing that a good lamp can be burned quite a few hours without changing its candlepower appreciably. The lamps at the Bureau of Standards, used to maintain the unit, are carbon filament lamps running at approximately 4 watts per candle. Their value in candles is given when they are burning at definite wattages. In ordinary use, however, the lamps are rated as having a certain candlepower at a stated voltage.

Voltage Control. — For accurate work, the voltage must be controlled to within 0.01 per cent for carbon lamps and 0.02 per cent for tungsten lamps. Experiments at the Bureau of Standards indicate that the lamps will give a constant value for a longer period if they are burned at constant wattage rather than constant voltage. In the use of tungsten lamps, the filament should be either welded to all supports or should have upper supports made in a spring form so that the contacts of the filament with the supports will be constant. In practical work, a number of the lamps are generally used and their average taken as a basis of computation. As soon as an individual lamp shows a value, relative to the mean, differing from that assigned to it by more than a given amount, it is discarded. While this method makes possible the detection of individual changes, there is nothing to indicate whether or not the group of lamps has changed slightly as a whole. Hence, it is highly desirable to have a satisfactory primary standard to serve as a check.

Heterochromatic Standards. — Within recent years, heterochromatic photometry has raised a new question in the problem of photometric standards. As long as the lamps to be compared have approximately the same spectral composition, different photometric workers get comparable and consistent results. But as soon as the color element is injected, as in the measurement of the new gas-filled tungsten lamps against carbon lamp standards, then discrepancies appear. Of course, the gas-filled lamp can be used as a working standard, but it must be calibrated.

Instruments

When a standard has been provided, instruments and apparatus must be available with which to make the measurements. Of the instruments, the photometer is naturally the most important.

Terminology. — The word "photometer" is sometimes used in reference to the apparatus as a whole, sometimes to a part which will be defined under the name "photometer-head." There is no unanimity in the terminology of the instruments and apparatus used in photometry. However, there is no necessity for confusion, and a little familiarity with the subject and a moment's reflection will make it possible to tell whether the apparatus as a whole, or a special part of it, is referred to. Where "photometer-head" is used, what is meant is that part of the apparatus which contains the photometric disk or screen and the means by which the disk is viewed.

Basis of Various Types of Photometer-heads. — Many kinds of photometer-heads have been devised. Most of them are based on the comparison of the brightness produced by the illumination of two contiguous surfaces. It would seem that almost every effect produced by light has been made the basis of a photometer, but with the exception of the type just mentioned, these are seldom, if ever, used. For descriptions, see the works of Palaz and Liebenthal. For all except special kinds of work, the intensity of a source is measured by comparing the brightness or contrast produced by the illumination of two adjacent surfaces, and the photometer-heads most widely used in this country are of the Bunsen or Lummer-Brodhun types.

Requirements for Accurate Instrument. — The eye is able to detect very small differences in the brightness of two adjacent surfaces, assuming for the time being that the sources compared are of the same color. In the use of photometers based on this principle, it is found that the greatest accuracy demands that the two surfaces observed be either actually immediately adjacent or made to appear so by optical means and arranged so that the dividing line between them disappears when

an equality of brightness has been reached. Hence, such photometers are sometimes called "disappearance" photometers. The principle employed is called the "equality" principle and this name is a general one also sometimes applied to the photometers themselves. The eye, by observing the merging of one field into another, can determine the point of equality, or the disappearing of the dividing line, with considerable accuracy.

Among the other requirements for an accurate instrument may be mentioned the symmetry of the two halves, so that light striking one side of the disk will not be subject to changing influences different from those encountered by light striking the other side of the disk and thus cause a different setting when the photometer is reversed.

Stray Light. — Another important factor is the protection from stray light, so that none may appear in the field of view as seen by the eye. Such light may be due to defective optical parts, such as cubes, prisms, mirrors, lenses, etc., or it may be due to poor construction of the enclosing box. The size of the field of view and the construction for observation by one eye or by both eyes are points upon which there is still no unanimity of opinion. In order to keep an instrument in good condition, it should be simple in construction and the optical parts should be readily accessible for cleaning.

Ritchie. — Because of the number of subsequent modifications of the idea, mention should be made of the Ritchie photometers. In one form, two mirrors throw the light from the two sources upon a translucent screen. It is difficult to make the mirrors so that their edges come together in a line. There has recently been described an instrument (Fig. 60) which is a modification of this type, using only one mirror, made by depositing platinum on plate glass by the cathode-discharge method. The glass is first scratched by a steel-wheel glass cutter and, when it is broken, a very sharp edge results. Each piece can be used to make a mirror.

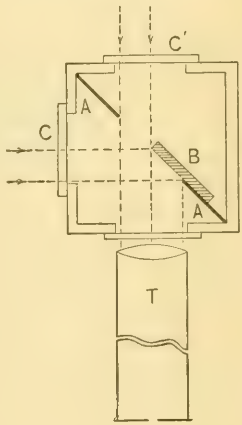


Fig. 60. Recent Type of Ritchie Photometer Head.

Wedge Type. — Ritchie's wedge photometer, in which the mirrors and screen are replaced with two pieces of white cardboard having good diffusing surfaces, is open to the same objection regarding the dividing line. Quite a number of photometers have been devised using the Ritchie idea, but very few have found any practical use; they are

all subject to the possibility of error due to the placing of the wedge in the photometric axis. If the wedge does not present the same obliquity on each side to the incident light, the effect of the cosine law is different and the error is apt to be magnified by the fact that the angle of the wedge is in general such that the cosine is varying rapidly. To judge from Trotter's work, Ritchie photometers have found quite wide use in England and, in certain special cases where a cheap instrument for "rough and ready" work is desired, they may prove very convenient. For a discussion of the best angle to use with the mirrors or cardboard and the errors to be expected, reference should be made to Trotter's book.

Contrast Principle. — In addition to being able to detect small differences in the brightness of two contiguous surfaces, the eye is also able to determine with great precision when the contrast between a dark and lighter portion of a surface is the same as that between a dark and lighter portion of another surface close to it. This is known as the "contrast" principle, and photometers in which it is applied are sometimes called "contrast" photometers. In such cases, the field of view seen in the photometer-head consists of at least four parts, two receiving light from one source, the other two from the other source, an absorbing device decreasing the flux received on one part in each instance.

In photometers using the contrast principle, the equality principle may also be employed, since, when the equality of contrast is established, equality of brightness is also observed. If this is not so, the construction of the apparatus is faulty.

Degree of Contrast. — The degree of contrast which gives the most sensitive arrangement depends somewhat on the illumination of the fields. It should be small in all cases, and smaller where very bright fields are encountered than where weak illuminations are used. However, it is fixed in the ordinary instrument and is usually about 8 per cent.

Bunsen

The Bunsen, or "grease spot," photometer in its various modified forms is the most widely used instrument of its kind, in this country at least.

Theory. — The theory of it is as follows: Suppose a piece of white paper, semi-translucent, a portion of which has been made more translucent by a drop of grease or wax, is held between two sources of light. An observer looking at one side will see one of three conditions: either the spot (Fig. 61) will appear brighter than the surrounding paper, or

it will appear dark on a white background, or it will be almost indistinguishable. If the paper is moved nearer one of the lights and the side observed is toward the light, the appearance of the spot will change so that if it was darker, it will become more so; if lighter, it will become less so; and a position will be found where it will almost, if not quite, disappear. This point does not in general, however, represent the position of equality of illumination on both sides of the sheet, for if the observer looks at the other side of the paper, a different position will be found where the spot disappears. This is due to the fact that all the light received by the spot does not pass through, and all received on the rest of the paper is not diffusely reflected but some is trans-

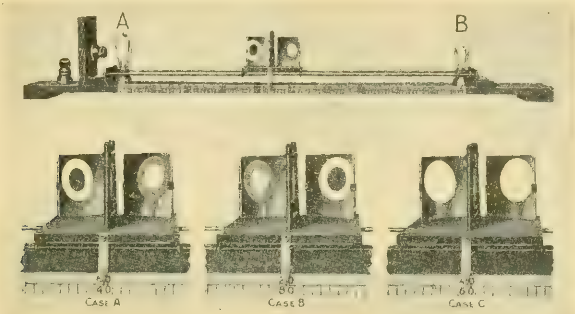


FIG. 61. Bunsen Photometer and Screens.
Case A — Screen at Left of Balance Point.
Case B — Screen at Right of Balance Point.
Case C — Screen at Balance Point.

mitted. What the observer sees then, on looking at one side of the sheet, is light coming from the source on that side, mainly diffusely reflected from the ungreased portion, some light reflected from the greased portion, as well as light from the source on the other side transmitted largely through the greased portion but partly through the ungreased. Since the reflecting and transmitting properties of the two sides are not likely to be the same, the position for equality of illumination will depend on which side is observed.

Equation. — The equations from which the relative intensities are computed may be derived as follows:

Let I_1 and I_2 be the intensities of the two sources; p_1 and t_1 be the reflection and transmission coefficients of the ungreased portions; p_2 and t_2 of the greased; r_1 and r_2 be the distances to the respective sources when the setting has been made while observing a given side of the disk; r_1' and r_2' be the distances when the disk has been reversed but

the observer looks at the given side which is now turned toward the other source. Then for the first position, the light coming to the eye from the ungreased portion will be

$$p_1 \frac{I_1}{r_1^2} + t_1 \frac{I_2}{r_2^2} \text{ and this is equal to } p_2 \frac{I_1}{r_1^2} + t_2 \frac{I_2}{r_2^2},$$

the light coming from the greased portion.

For the second position:

$$p_1 \frac{I_2}{r'^2_2} + t_1 \frac{I_1}{r'^2_1} = p_2 \frac{I_2}{r'^2_2} + t_2 \frac{I_1}{r'^2_1}$$

from which

$$I_1 = \frac{r_1 r'_1}{r_2 r'_2} I_2.$$

As ordinarily used, the Bunsen photometer-head is provided with two mirrors which enable the observer to see both sides of the disk simultaneously. In this case, the observer may see a contrast between the greased and ungreased portion and the photometer-head is adjusted until the contrast on the two sides appears the same.

Sensitivity. — The sensitiveness of the disk, as well as the accuracy of the results obtained by its use, depends to a great extent on the method employed in constructing it. Three conditions must be fulfilled by a good disk: (1) The two sides must be alike; (2) the contrast between the greased and ungreased portions must be such as to give the proper degree of sensitiveness for the work in hand; (3) the paper and the grease must exercise no selective absorption or reflection effect on the light.

The above discussion assumes a partially transparent unglazed portion, but this transparency is not necessary to the theory; and if the Leeson disk (see below) is used, the part surrounding the star may be absolutely opaque. Under these conditions the computation is exactly similar for the reversal of the disk. However, if contrast is desired, then transparency is necessary and the degree of contrast can be regulated. In this case, the light transmitted through the unglazed portion must be more than that reflected from the glazed part.

Disk Making. — Various procedures have been recommended for making disks. A piece of copper, round or star-shaped, may be plunged into a bath of molten wax, held there until heated, and then pressed on the paper until the wax has completely penetrated it. The excess of wax should be removed by scraping or by laying on it a piece of blotting paper and pressing with a hot iron. Heavy, unsized white

paper, such as white drawing paper, should be used. For other methods, reference should be made to the various books on photometry.

Leeson Disk. — A type called the Leeson disk is made by pasting sheets of thin, translucent paper to each side of a piece of heavy paper in which a slender pointed star has been cut. The inner paper may be the same as that used in the grease-spot disks. The outer paper is selected to give the right degree of contrast and should have an unglazed surface. It was formerly possible to purchase such disks, not pasted together. Thin starch paste should be used and great care taken to be sure the parts adhere without wrinkling at the points of the star.

Rüdorf Mirrors. — The use of two mirrors, by means of which the two sides of the disk can be observed simultaneously, is credited to Rüdorf, and they are called Rüdorf mirrors. They are generally placed vertically behind the disk and so that their edges do not cast shadows on it, and should be inclined at an angle of 140 degrees to each other. With the disk they should be mounted in a box with the sides cut away to admit light from the sources to be compared and with an opening in the front through which to observe the disk. Modifications of the Rüdorf arrangement have been made by Von Hefner-Alteneck and Krüss.

Sources of Error. — It rarely happens that a disk has the same properties on both sides. Hence, when using the direct method, measurements should be made with the screen first in one position and then turned through 180 degrees by a rotation of the photometer-head. Another source of error is that ascribed to differences in the eyes of the observer, so that there is a tendency to set the photometer persistently in one direction. This can be avoided by working with one eye covered, or by the use of a method due to Krüss.

Advantages. — Among the advantages of the Bunsen photometer-head, aside from its accuracy, are its simplicity and cheapness. Another advantage lies in the fact that it can be used with both eyes, and in factory work this is considered quite a help. Its principal disadvantage is the difficulty of getting satisfactory disks where high accuracy is desired. Theoretically, there is the objection that each side of the screen shows light from both sources.

Lummer and Brodhun Photometer

The next most widely used photometer-head is known as the Lummer and Brodhun photometer. It is one of the most sensitive, and is considered by many the most sensitive type of instrument. It is extensively used both for precision and for technical photometric work.

Cube. — The most essential part of it is what is called the Lummer and Brodhun "cube." It is really an ideal Bunsen disk and may be used either as an "equality" or contrast instrument. In the former case, the cube consists of two right-angle prisms with their hypotenuse faces placed together, the edges of the face of one having been ground away so that only a small circular portion of that face is left. The two prisms are clamped together so tightly that all air is excluded from between the parts in contact. Consequently, over this small circular area the two prisms become optically homogeneous and light will pass through from one to the other without diminution. The rest of the photometer-head (Fig. 62) consists of a plaster-of-Paris screen, S, which receives the flux from the two sources to be compared; two mirrors, m and m', which reflect the diffused flux to the cube, C; a magnifying lens, L, by means of which an image of the hypotenuse surface is focused on the eye of the observer at E.

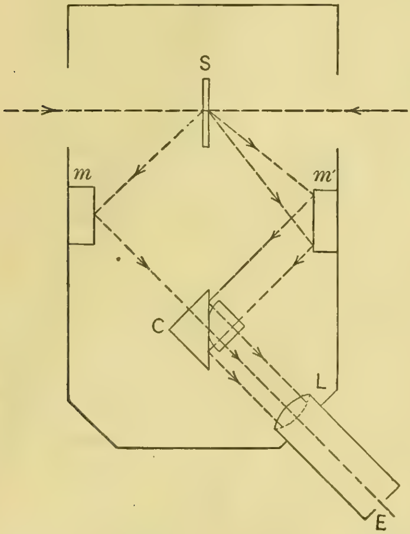


FIG. 62. Diagrammatic Sketch of "Equality" Type of Lummer and Brodhun Photometer-head.

Action of Cube, Equality Type. — The action of the cube is as follows: The flux received on the left of S is diffusely reflected and a part is intercepted by the mirror, m, and reflected into the cube. That portion of this beam striking the central contact surface passes through and into the eye. But that part which strikes the rest of that surface is internally reflected and sent out in other directions. The flux from the right-hand side of S, which after reflection from m' strikes the central contact portion of the hypotenuse surface, passes through and out into space. But that part which strikes the rest of the surface is, internally, totally reflected into the eye. Thus the eye sees an inner circle by light coming only from the left side of the screen and an outer ring by light coming only from the right side of the screen. And so it is evident that the arrangement makes an ideal Bunsen photometer in which the inner circle corresponds to the grease spot, and there is perfect transmission, while from the surrounding ring there is perfect reflection, each portion of the field being illuminated solely by the light from one source. When

the two sides of S are equally illuminated, the line of separation between the circle and the ring should disappear, provided the sources to be compared are of the same color. If not, there will still be a tendency for it to disappear if the color difference is not too great.

The prism, mirrors and screen are contained in a light-tight, internally blackened metal box which has openings on the sides to admit light to the screen or disk and another opening for the eye-piece, containing the magnifying lens. The box can be turned about a horizontal axis so as to reverse the disk, and in some types is provided with a graduated circle at the back for use in distribution-curve measurements.

This instrument is known as the Lummer and Brodhun " equality " or " match photometer-head " and is made up in a number of different forms, and the " cube " is used in various other instruments. The mirrors may be replaced by totally reflecting prisms.

Contrast Type. — In the " contrast " type, Fig. 63, the cube is arranged as shown in the cut, Fig. 64. In this form the hypotenuse surface is etched away at *de* in the form of a trapezoid or segment and at *bc* and *aA* so as to form a trapezoid or segment of unetched glass at *ab*.

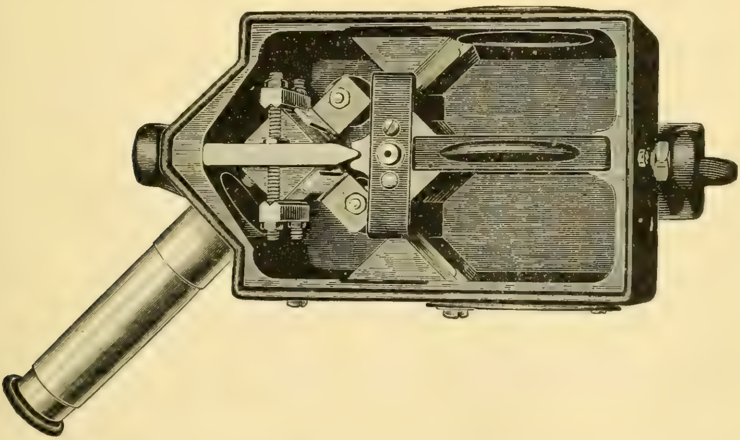


FIG. 63. Photometer-head Showing Top Removed.

The light from the left-hand side of S (see Fig. 62), reflected from m, is transmitted through the spaces Ce, dc and ba, and reflected from ed, cb and aA. Similarly the light from the right-hand side of S, reflected from m', is again reflected at aA, bc and ed, and transmitted at ab, cd and eC. Thus each trapezoid or segment is illuminated by light from one side and one side only, and is surrounded by a surface receiving light from the opposite side. The absorption strips at F and E cut down the light

reaching the trapezoids or segments, so that as a balance is approached they appear darker than their surroundings, and when there is equal illumination of both sides of *S*, the center line of division disappears and the two trapezoids or segments appear equally sharp and dark against their backgrounds. As the photometer-head is moved one trapezoid or segment becomes darker; the other becomes lighter, tending to disappear. The absorption strips are pieces of plane, parallel clear glass which by reason of reflection from their surfaces produce an effective diminution in the light of approximately 8 per cent.

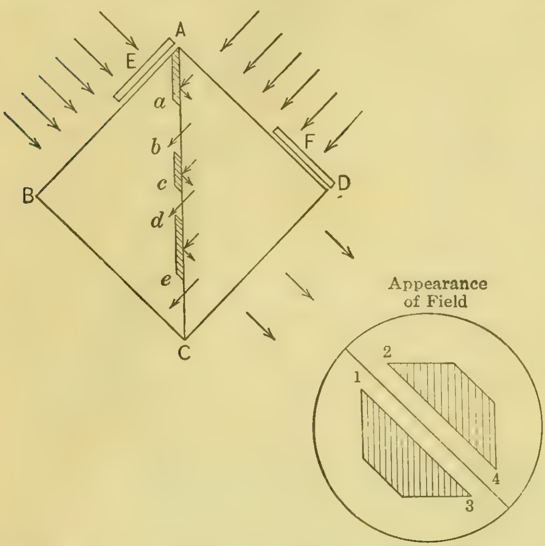


FIG. 64. Schematic Diagram of Lummer and Brodhun Photometric Cube, Contrast Type.

Sensitivity. — Since the eye is able to perceive a smaller degree of difference in contrast than difference in brightness, the contrast form is more sensitive than the equality or disappearance form. Both are more sensitive than the Bunsen, since in the latter a mixture of the light from the two sources is always present in the grease spot and sometimes in the surrounding field. Lummer and Brodhun in their original experiments found that a contrast of about 3.5 per cent gave the greatest accuracy for illuminations ordinarily met in practice. Since, however, clear glass, as stated, has an effective absorption of 8 per cent and the instruments based on the contrast principle have employed small glass strips to produce the effect, 8 per cent has become the usual contrast. There has been devised an arrangement whereby, by making the glass strip wide enough to cover the entire face of the cube, an extra strip having an absorption of 3.5 per cent can be cemented on by Canada balsam over the part where the contrast is desired, and a 3.5 per cent contrast is thus obtained. Instruments fitted out in this way have given more accurate results than the regular type with 8 per cent contrast. A further increase in the sensitiveness of the Lummer and Brodhun contrast photometer can be obtained by graduating the absorption of

the contrast strips from top to bottom, making them, say, 1 per cent greater at the top than at the bottom for the one and the same amount less at the top than at the bottom for the other. Assume that the eye can detect a difference just greater than 1 per cent. Then a motion to the right of the position of balance would show a difference of more than 1 per cent at the top; motion to the left, more than 1 per cent at the bottom. Hence, a setting at the point midway between would make a reading certain to 0.5 per cent.

When there is an appreciable difference in color between the sources to be measured, no disappearance of the dividing lines occurs in the Lummer and Brodhun cube, and many observers feel that the Bunsen photometer is more sensitive. The results of some tests on the accuracy obtainable with different photometers are given in the following table:

	Per Cent
Lummer and Brodhun Contrast	0.38
Marten's	.46
Lummer and Brodhun Equality	.59
Joly Diffusing	1.7
Bunsen (Rüdorf Mirrors)	2.0

Auxiliary Apparatus. — The photometer-head is usually mounted on a carriage which can be moved back and forth on a track, called the photometer track or ways (Fig. 65, left side). The photometer carriage should be able to move easily and yet have as little lost motion as possible. It should carry a small shaded light which can be used to illuminate the scale when the position of the photometer is to be read.

Ways. — The ways should be rigid, not easily jarred, as straight as possible, and so constructed that the carriage will move in a straight line. The above applies to the case where the photometer carriage moves. In some types of photometric equipment the photometer-head is stationary and the comparison or the standard-lamp carriage moves. The movable carriages should be provided with pointers which travel over a scale attached to the ways.

Scale. — The photometer scale may be calibrated for distance readings, in centimeters or inches, or directly in candles. In the latter case, in incandescent lamp work a number of different scales to be used with different sizes of lamps are sometimes mounted on a drum which can be rotated so as to bring any desired scale under the pointer.

Screening System. — In order to be certain that any light which reaches the photometer disk, other than that from the lamps to be measured, shall be negligible, a screening system (Fig. 66) is usually employed. If this system is properly designed, it is not necessary to darken the walls of the photometer room. The screens should be

mounted on holders which will enable them to be moved along the track, and a number of them should be placed between the photome-

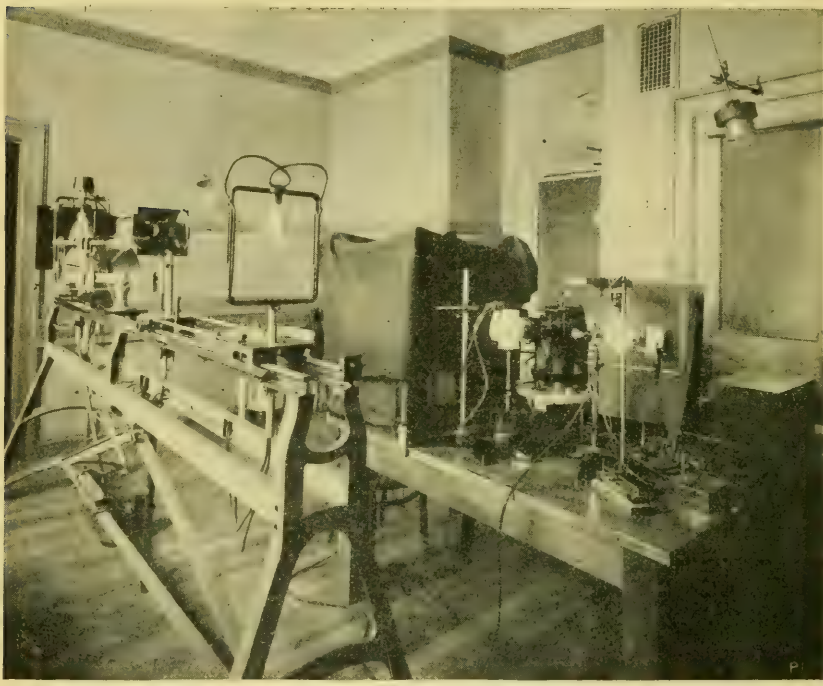


Fig. 65. Photometer Bench (left) and Spectrophotometer (right).

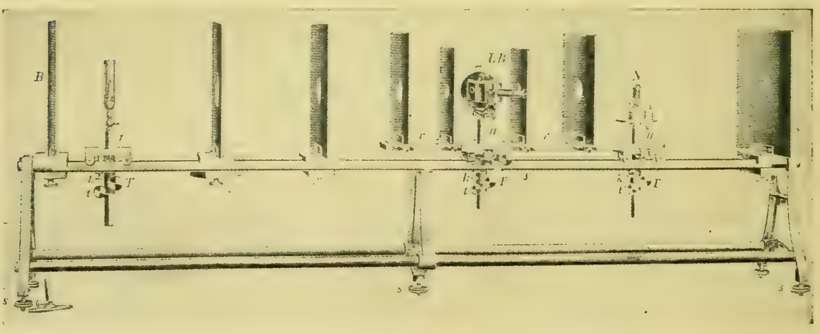


Fig. 66. Photometer Bench Showing Screening System.

ter-head and the lamps at the ends of the track. Each screen should have a hole cut in it, those farthest from the photometer having the largest hole. Back of each lamp should be placed a screen without

a hole in it. The best material to cover such screens is a good grade of black velvet. To be sure that no stray light is reaching the photometer disk, remove the disk and look through the photometer-head. The eye should then see only the light source and the black surfaces of the screens. The reflection from these surfaces, as long as dust is not allowed to collect, is negligible. Another method of making sure the screens are properly placed is to look past the edge of the screen and see whether the photometer disk is visible. If it can be seen from any point outside the screening system, then the screening is not sufficient. In commercial work, black paint is generally good enough to use on the screens, and in some cases it is desirable either to paint the walls of the room a dead black or to enclose the photometer completely.

The other auxiliary apparatus which is used will be considered in discussing " Methods."

Illuminometers

The photometer-heads previously described are in most cases used to measure candlepower or luminous intensity. Modifications are found in a class of instruments which are sometimes called " illuminometers," and sometimes " portable photometers," and which are employed primarily to measure illumination (Fig. 67). Because of their adaptability to so many classes of photometric work, they are also called " universal " photometers. These instruments should be, and ordinarily are, portable and can be used to measure candlepower (usually with less accuracy than the other type) and brightness as well as illumination. The essential parts of the best modern types are comprised in a reliable light source with means for controlling its candlepower; a translucent diffusing screen to receive illumination from it and a means of varying the illumination either by motion of the lamp or screen, or the interposition of absorbing devices; a suitable scale for recording these variations; another diffusing screen to receive the flux to be measured and capable of rotation about one or more axes; an optical system for bringing into juxtaposition in the field of view the surfaces of the two screens and an eye-piece through which to view them; a diffusing plate, called a test plate, used to place at a point where illumination is to be measured; a system of absorbing devices to cut down the test flux and thereby increase the range of the instrument; a suitable standard or tripod on which to mount it.

Sharp-Millar. — The first American-made instrument to come into general use was the Sharp-Millar (Fig. 68), which is typical of this class of photometers and a modification of a German design known as

the Weber. It consists of a rectangular hardwood box about 2 feet long, fitted at one end with an opening containing an elbow tube and at the other with binding posts for the electrical connections. On the

FIG. 67. Types of Portable Photometers (Approximately to Scale).

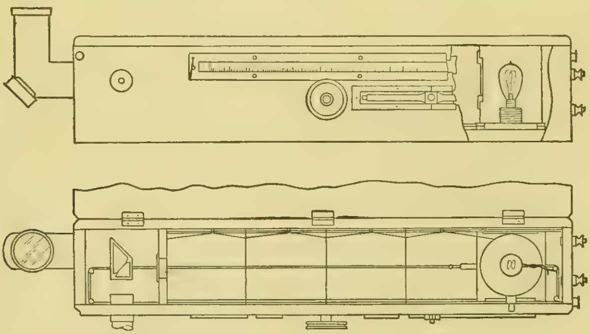


FIG. 68. Side Elevation and Plan of Sharp-Millar Photometer.

front at the elbow end is an adjustable eye-piece, and running along near the top, a translucent photometric scale graduated according to the inverse square law. In addition, the front holds a knob for moving the working standard lamp and a pair of resistances to control this lamp.

The lamp is mounted on a carriage and is moved on ways by means of pulleys and a cord connected to the knob. A set of movable screens, automatically adjusted with the motion of the lamp, acts to cut off stray light. Light from the working standard illuminates a small ground-glass plate which forms the equivalent to one side of the photometer-head disk. The other side is formed either by a diffusing plate at the elbow when the instrument is used to measure candlepower or brightness, or by a diffusing plate or translucent diffusing cap at the end of the elbow tube when the instrument is used to measure illumination. The photometric device is a modified Lummer and Brodhun prism in which, by addition of another totally reflecting surface, rays from opposite directions are brought to the sight tube. The elbow tube may be turned about a horizontal axis, and the diffusing plate at the elbow has on its reverse side a mirror which is used for candlepower and brightness measurements. The range of the instrument is extended by a pair of absorption glasses so fastened that either one of the pair may be used to cut down the light on either side of the prism. A smaller instrument has been designed.

Macbeth. — The Macbeth illuminometer is another American instrument of more recent design but of the same general character (Fig. 69). It is much more compact, the case being a small metal

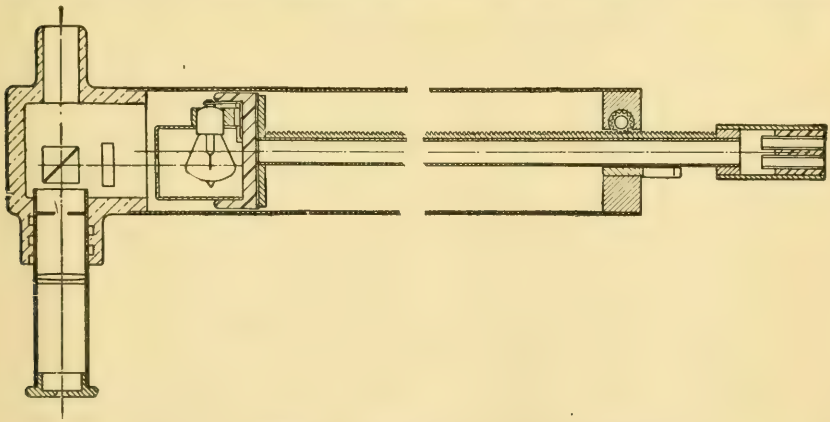


FIG. 69. Diagrammatic Sketch of Macbeth Illuminometer.

cylinder, and the working standard lamp is set at one end of a rectangular metal rod which contains the scale on one face and is moved by a rack-and-pinion controlled by a knurled knob. The interior of the tube is covered with black velvet to eliminate the effect of stray light and the rigid connection between the lamp and the scale avoids back-lash errors. The elbow tube is fitted with a mirror only, at the

elbow, the whole tube being removed for measurements of candlepower and brightness. A feature of this instrument is an auxiliary leather case containing resistances, dry cells, and a milliammeter, with an arrangement for checking the calibration of the working standard *in situ.*

Weber. — A foreign instrument, which was the precursor of precision instruments of this type, is the Weber photometer. In Fig. 70 the lamp shown as a standard is a benzine flame, but this can be, and in this country generally is, replaced by a miniature electric lamp. The difficulty with the latter is the necessity of adding to the equipment a battery (a dry or storage cell), a resistance, and a voltmeter or ammeter. This, of course, involves additional weight. The question of what to use for this comparison source has been much discussed, but the electric lamps seem to be the only solution where accurate work is to be done. The flame height has such an effect and is so hard to control in oil lamps that they are not satisfactory for precision work.

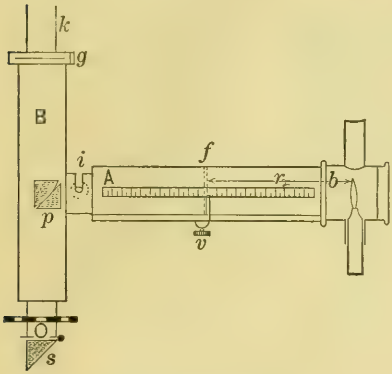


FIG. 70. Diagrammatic Sketch of Weber Photometer.

Referring to the figure again, the source at b illuminates a milk-glass plate, f, which is moved back and forth in the tube, A, and carries with it a pointer moving over the scale. Tube A is mounted on and can be turned about a vertical rod. Tube B is fastened by a sleeve to A and can be turned about a horizontal axis. At p is a Lummer and Brodhun cube and this is observed through the eye-piece at o. The other end of B has a holder, g, in which may be placed any one or more of a series of milk-glass plates. Beyond the holder is a tube, k, to protect g from stray light. If the instrument is to be used to measure the candlepower of a source, tube B is pointed at the source and oriented so that its axis extended passes through the center of the light source. The milk-glass plate at g and the other at f then become the two surfaces which correspond to the sides of the plaster-of-Paris screen in the ordinary Lummer and Brodhun photometer-head. The distance from the source to the plate at g having been measured, the intensity can be calculated from the reading of the scale, the latter having been previously calibrated. Thus, if it were calibrated in milliphots and the unknown source was at a distance of 1 meter from g, and if

equal illumination was found with f at 1 milliphot, then the source would have 10 cp. in the given direction.

Measurement of Illumination. — If the instrument is to be used to measure illumination, the plate at g is removed and one of two procedures is followed. In one procedure, a white diffusing plate or card is placed at the point where the value of the illumination is desired, and tube B is pointed at this plate. This plate would then be seen in place of the plate at g, and f would be moved until the photometer field showed uniform brightness. The scale having been previously calibrated, the pointer would indicate the correct illumination.

In the other procedure, a strongly diffusing milk-glass plate is fastened on the end of g in place of the tube, k. The instrument is then placed so that this plate occupies the position where the value of the illumination is desired. If it is in a horizontal plane, a totally reflecting prism at s enables the observer to see the prism, p, without effort. As before, f is moved until the photometer field is of uniform brightness.

The range of illumination which the instrument can measure is extended by using a number of plates at g or single plates of varying density.

Beckstein. — Another foreign instrument of a more elaborate type is that due to Beckstein (Fig. 71). The standard lamp is placed in a small opaque sphere having a whitened matte inner surface and provided with a window made of milk-glass which is shielded from the direct rays of the lamp. The transmitted light may be altered in intensity by means of an absorbing screen or changed in color by a glass filter and then passed through a variable-opening sector-disk arrangement, g, to a photometer cube. In this type of sector-disk, which will be referred to later, the beam of light is made to rotate. It passes through a sector opening, which may be adjusted, while the light is rotating, from an opening of 180° to zero. A suitable scale is attached. Thus, the light from the standard lamp sphere may be altered continuously from 50 per cent to zero, and an additional fixed reduction may be made with the absorption strip mentioned above. The figure shows the original form of the instrument, the cylindrical housing, TO, having subsequently been replaced by the small sphere. The receiving plate of translucent milk-glass is attached to a tube, G, which houses two absorbing devices, g_3, which may be adjusted to cover quite a large range in illumination. The tube, G, can be turned to any desired position and the instrument used as an ordinary photometer by placing the shielding tube, h_3, over the milk-glass plate, when the latter is in the position shown. For brightness measurements, the arrangement is the same as far as h_3 is concerned, but the shell carrying the milk-glass plate is

turned until an unobstructed opening is in line with h_3. The sector-disk is driven by a motor and current must be provided to operate it.

In England a number of illuminometers have been developed in which the illumination due to the standard lamp is varied by changing the angle of incidence on the translucent screen. An excellent description of these instruments is to be found in Trotter's work.

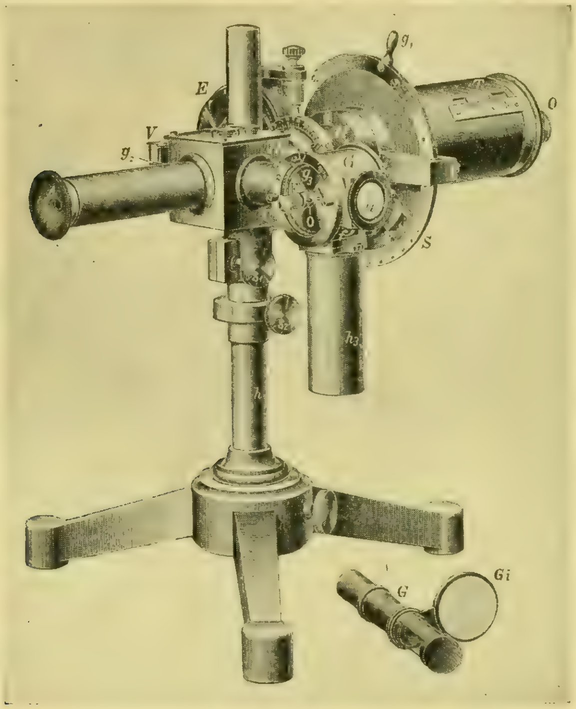


FIG. 71. Beckstein Illuminometer.

Foot-candle Meter. — In order to make it possible to obtain approximate values of illumination quickly and easily, an instrument called a foot-candle meter has been devised on the same principle as Trotter's slot or limit gage photometer. As shown in Fig. 72, it consists of a light box covered with a screen perforated with a number of small holes lying in a straight line, and covered with a translucent diffusing material. When the interior of the box is illuminated by a small incandescent lamp placed at one end, the spots nearest the lamp appear brightest as viewed from above, and there is a graduated decrease in brightness to the spots farthest from the lamp. The instrument is placed at or near the point where the illumination is desired and the spot which has that illumina-

tion will tend to disappear. The foot-candle value may be read from an attached scale. The case carries two dry cells, a voltmeter and resistance, and the whole is small enough to be easily carried by hand and used in restricted locations.

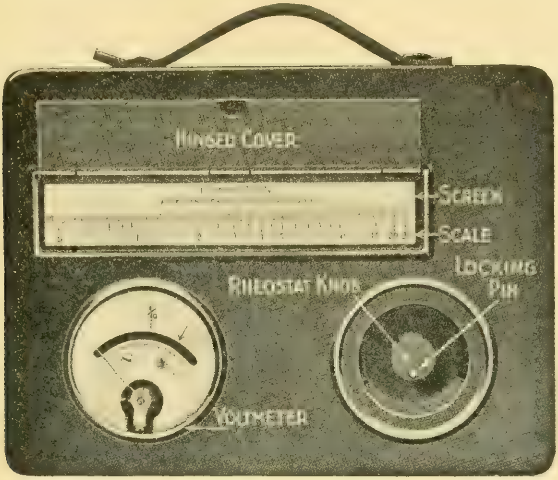


Fig. 72. Foot-Candle Meter.

Sources of Error. — The receiving plate is one of the essential parts of an illuminometer photometer. In making measurements, the photometric device must either be placed under it or over it. If below the plate, the extent to which the surface obeys Lambert's cosine law and the extent to which the diffusely transmitted light is affected by the glass are factors of considerable importance. If the photometer box is above the plate, conformity to the cosine law is equally important, but the extent to which the instrument and the observer cut off light which would otherwise reach the plate must also be given careful consideration. Where the receiving plate is kept as part of the instrument, interference with the incident flux is much more easily avoided. Several attempts have been made to produce a test plate in which the cosine error is corrected; among others, one called a "compensated test plate" both in the reflecting and transmitting form. In the latter case (Fig.

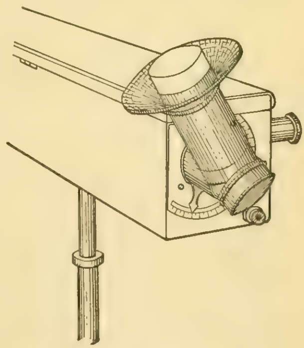


Fig. 73. Compensated Test Plate.

73), the light lost by reflection at increasing angles of incidence is compensated by admitting light to the posterior side of the plate through an opal glass ring. In the reflecting form, a disk of depolished white glass is used and additional light added by transmission of light diffused from a plate placed beneath.

As most illuminometers are direct-reading, the scale is a potential source of error. The constancy of the standard lamps and stray light caused by leakage or by internal reflections are other possible sources. Proper calibration will reduce these errors in general to the point where they are negligible compared with the uncertainties in the photometric settings.

Methods

Direct Comparison. — There are two *general* modes of procedure employed in the intercomparison of light sources by the use of photometric apparatus. In the first, which is known as the " direct comparison " procedure, the apparatus is set up in such a way that the source of light to be measured is compared directly with the standard source, one being placed on one side of the photometer-head and the other on the opposite side, and a balance obtained in the usual way. In making measurements according to this procedure, many precautions are necessary to eliminate errors such as differences in the two sides of the photometer disk and other parts of the photometer-head, inequalities in the ways, errors in the scale, stray light reflected from the screening surfaces, and the tendency for an observer to favor one side of the disk rather than the other. This method is quite commonly used in gas testing.

Substitution. — The second general procedure is known as the " substitution " procedure. In this case, the comparison between the source of light to be measured and the standard is indirect. First, the standard source of light is set up and compared with a constant source of light of convenient candlepower and color. Then the standard source of light is removed and the unknown source is substituted for it. The unknown source is then compared with the constant intermediate source of light and its value is computed from the two sets of measurements. The advantage of this procedure over the direct comparison method lies in the elimination of all errors due to lack of symmetry, etc., since these errors appear in both measurements, that of the standard and that of the unknown. The substitution procedure should be used whenever possible.

Means of Varying the Illumination on the Photometer-disk. — In order to get equality of illumination on the sides of the photometer-disk

and hence in the field of vision, a means must be provided for changing this illumination in a known manner. The simplest and most common method is to vary the distance between the photometer and one or both sources. This may be accomplished in three ways: (*a*) by having the sources fixed and moving the photometer between them; (*b*) by keeping one source and the photometer fixed and moving the other source; or (*c*) keeping one source fixed and moving both the photometer and the other source simultaneously, the latter source being fastened to the photometer-head by connecting rods.

Equations. — If the photometer carriage or either source is moved, its motion should be parallel to the photometric axis. In the direct comparison procedure for condition *a*, let E be the illumination on both sides of the disk. Let I be the candlepower of the source on the left and r its distance from the photometer-head. Similarly, let I_1 be the candlepower of the source on the right and r_1 its distance. Then

$$E = \frac{I}{r^2} = \frac{I_1}{{r_1}^2} \qquad \text{or} \qquad I = I_1\left(\frac{r}{r_1}\right)^2.$$

If a second reading is made with the disk reversed — and this should always be done for even fairly accurate results — then, as was shown in the theory of the Bunsen disk, $I = I_1 \frac{rr'}{r_1 r_1'}$. If r and r' are very different, the disk should be examined and, if necessary, replaced.

Not infrequently it is desirable to keep the photometer-head stationary and at a fixed distance from one source, I, say the unknown (condition *b*). In this case, the comparison source, I_1, is moved and the candlepower ratios are as before except that, r being constant, $I_1 r^2$ is a constant, therefore $I = \text{constant} \times \frac{1}{{r_1}^2} = \text{constant} \times \frac{1}{r_1 r_1'}$, where the disk is reversed. In the third arrangement (condition *c*), one source, I_1, say the known, is rigidly attached by means of rods connecting the carriage to the photometer and both photometer-head and source move together, the other source, I, being fixed in position. Then $\frac{I_1}{{r_1}^2}$ is a constant and $I = \text{constant} \times r^2 = \text{constant} \times rr'$ where disk is reversed. One advantage of fixed distance between the photometer and one source is that the inverse-square-law error can be eliminated under certain conditions even though the distance involved is small.

If the **substitution** procedure is used, the lamp used as an intermediary is sometimes called the comparison lamp. Call its candlepower I_c and its distance from the photometer disk r_c. Then for condition *a*, if I_s is the intensity of the standard lamp, r_s its distance, I the intensity of the

unknown, r its distance, $I_s = I_c\left(\frac{r_s}{r_c}\right)^2$, $I = I_c\left(\frac{r}{r'_c}\right)^2$. From which $I = I_s\left(\frac{rr_c}{r_s r'_c}\right)^2$, if the disk is not reversed.

In condition b, $I = I_s\left(\frac{r_c}{r'_c}\right)^2$ and in condition c, $I = I_s\left(\frac{r}{r_s}\right)^2$. Where the disk is reversed, the equations should be altered as before. Obviously, then, the last two arrangements are to be used if possible. A fourth arrangement, which is available and sometimes used, is to move a mirror or a pair of mirrors. But the principle is the same. To avoid confusion in all cases, work from the equation $E = \frac{I}{r^2}$

Rotating Sectored Disk. — The illumination on the photometer disk can be changed by intercepting the light beam with a rapidly rotating disk having sector openings cut in it. These disks should be so constructed and should be rotated at such a speed that no evidence of flicker appears in the photometric field. To facilitate this the openings are generally arranged symmetrically so that the intervals between the passing of an open sector and the next open sector will be the same. Several types of rotating sectors are in use.

Fixed Opening. — The fixed-opening sector, Fig. 74, provides a convenient means for reducing the flux of a beam of light in a known ratio, an operation which is often desired in order to bring a given measurement within the range of a given photometer bar. For instance, in measuring a 1000-watt lamp, a 12° disk will bring the candle-power to approximately 33.4, which can be measured with an ordinary 40-watt lamp as a standard and with the photometer-head at the center of the scale. In commercial photometry, both 60- and 30-watt lamps can be measured without changing the comparison lamp, if a 180° disk is used. With two sets of three sectors having percentage openings of 50, 60 and 70 respectively, it is possible by combining two at a time to get percentage openings of 10, 20, 30 and 40, and such sets can now be purchased.

If two disks, each having a total opening of 180°, are arranged on the same axis so as to permit one to be moved with respect to the other, it is possible to get any ratio from 50 per cent to 0 by changing the amount of the shift. Using two disks, the maximum opening can be made greater than 50 per cent by making the closed portions in sections which can be spread open like the leaves of a fan. Types of two-plate disks have been developed recently.

Brodhun or Rotating Prism. — A third type, illustrated by the Brodhun sector, Fig. 75, permits of a change in the opening while the in-

strument is in operation. In this case, the beam is rotated past a stationary sector, D. Two Fresnel prisms, gg_1, h_1h_2, are employed for this purpose and the percentage opening is read from an outside scale. As at present constructed, the instrument is adapted to intercept

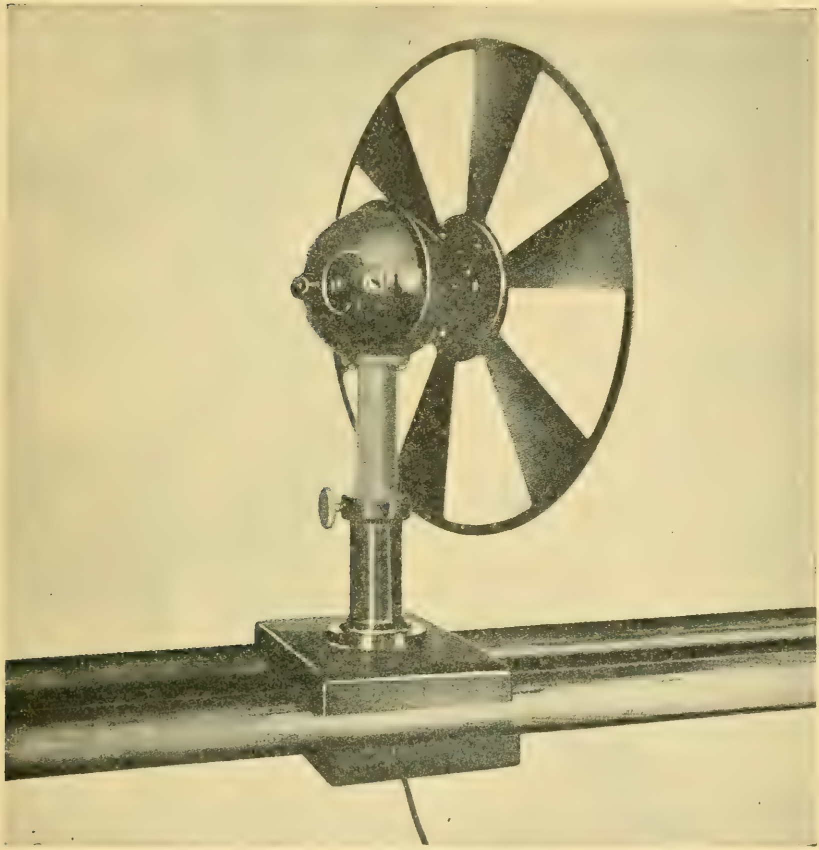


FIG. 74. Sectored Disk Mounted on Photometer Bar.

light flux in rather small beams, such as those used with spectroscopic apparatus.

Variable-sectored Disk. — For the special purpose of spectrophotometry, in which the beam to be measured enters the narrow slit of the collimator, there has been devised (Fig. 76) a simple form of disk in which the opening used can be varied while the disk is rotating. In this form the sides of the apertures are not radial but parts of a circle, and so arranged that near the center of the disk the total opening is almost 90 per cent, while it decreases to practically zero at the periphery.

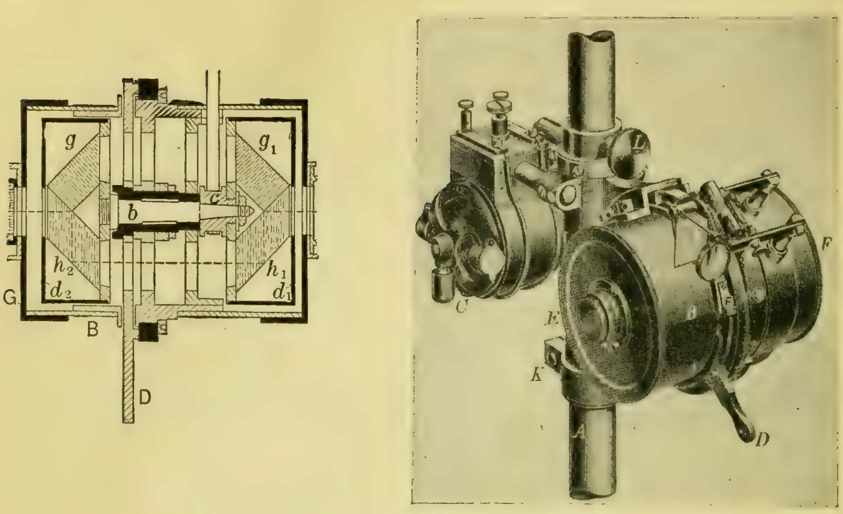


FIG. 75. Brodhun Sector Disk.

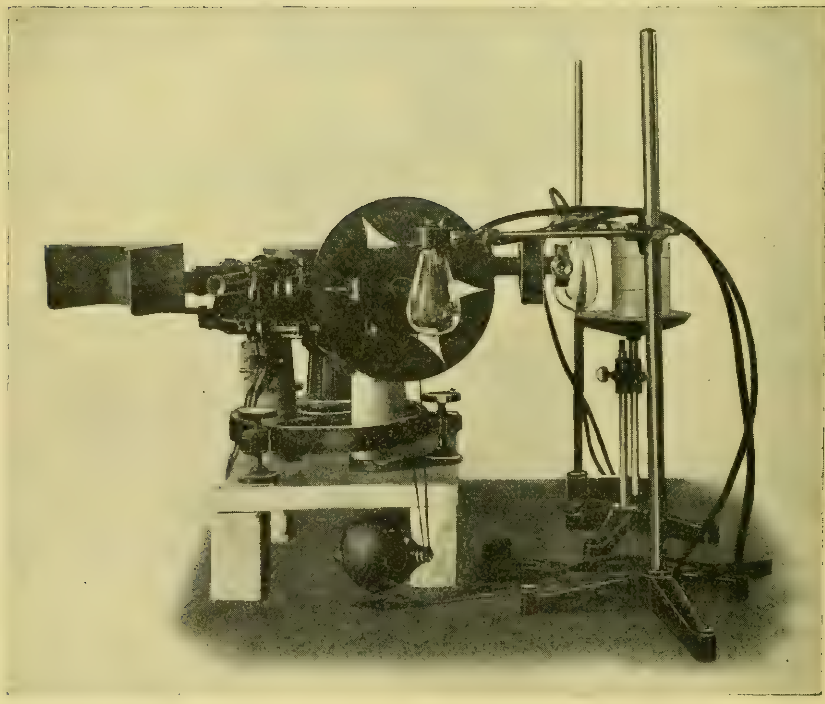


FIG. 76. Variable-sectored Disk, Mounted on Spectrophotometer.

Thus, by moving the axis of rotation of the disk back and forth laterally, the opening in front of the slit is changed while the disk rotates, and a suitably calibrated scale indicates the effective transmission. Obviously such a disk can be used only where the beam is very small, since otherwise the transmission on one side of the beam would materially differ from that on the other.

In all cases where disks are used, care should be taken to see that the entire beam is included within the radial opening of the disk. Assuming the disk to be large enough initially, this can be accomplished by seeing that the disk is placed close enough to the photometer-head.

Diaphragms. — If the source of light is a uniformly diffusing surface, the amount of light it emits is proportional to its area, and if a diaphragm is placed before it, the light transmitted will vary as the opening in the diaphragm. Thus if a uniformly diffusing surface, such as a block of magnesium, is placed in front of the slit of a spectroscope and illuminated uniformly, the light which gets into the spectroscope will vary directly with the opening of the slit. Again, if a converging lens is used to throw an image of the bright surface which is the source of light on the photometer disk, then the lens diaphragm may be used to alter the intensity of the transmitted beam.

Absorbing Media. — A fourth method of varying the illumination by a known amount is by the use of absorbing media. It is essential that such media be as non-selective in their absorption as possible. Smoked glass is quite generally used for this purpose but is somewhat selective.

An absorbing device called a neutral tint-absorbing screen, which is free from the selectivity error, consists of ruled gratings such as those used by photo-engravers. They are simply pieces of glass with black lines etched on them, and transmissions from about 80 per cent down to 10 per cent can be obtained by a proper choice of ratio of opaque to clear spacing, size and fineness of the spacing. Each of these absorbing screens should be calibrated under working conditions. If two such black line gratings are properly mounted so that one can be moved with respect to the other, the transmission can be made to vary continuously. This method of changing the illumination is of particular value in cases where rotating sectored disks cannot be used, as in flicker photometry.

Besides the above-mentioned methods for varying the illumination on one side of the photometer-head disk, others have been suggested and are sometimes used, as, for instance, varying the angle at which the source is observed; or in incandescent lamp photometry, varying the voltage on the lamp; or in gas photometry, the height of the flame. But these are not used with sufficient frequency to warrant discussion.

It should be noted, however, that in varying the voltage of an incandescent lamp, the color is also varied and this is apt to be objectionable.

Candlepower Measurements in Various Directions. — The quantity to be measured will in general determine the course to be followed in making the measurement.

Center of Radiation. — For candlepower in one direction, the lamp should be mounted so that the given direction coincides with the photometric axis or, if this is not possible, so that the direction is normal to the photometer disk or makes an angle which can be duplicated for the light coming from the comparison source. One of the difficulties in the single-direction type of measurement is to determine the proper point in the illuminant from which to measure the distance to the photometer-head disk. This point is called the center of radiation. In the case of an incandescent lamp, it may be taken as lying on the axis of the lamp (in general, a line passing through the center of the base and the center of the filament construction). In the case of a rotating lamp, the center of radiation will be so close to the axis of rotation that it can be assumed to be on this axis for all practical work. But in accurate work this point should be mentioned and the distance at which the measurement is made, specified.

Mean Horizontal Candlepower. — To measure the mean horizontal candlepower, only a single measurement is necessary if the lamp can be rotated. Otherwise, either a system of rotating mirrors should be used, or a sufficient number of measurements in different directions or at regular angular intervals in a horizontal plane must be made to give a good average. In such point-by-point measurements, if the lamps show a marked change in candlepower in a given region, additional measurements should be made in that neighborhood. The mean horizontal candlepower is measured practically only in the case of incandescent lamps. When measurements are made with a lamp rotating there will be in most cases a continuous fluctuation of the illumination on the photometer disk, due either to variation in the candlepower in different azimuths, or to the filament not being properly centered in the bulb and with respect to the base, so that the distance from the filament to the disk changes during a rotation.

Elimination of Flicker. — This fluctuation causes an appearance of flicker in the field of view. If this flicker is marked, it is very difficult to make a judgment of the equality of illumination. The flicker can be reduced to the point where it is not objectionable by making the speed of rotation high enough. It can also be decreased by the use of a single auxiliary mirror placed near the lamp and adjusted so that, in addition to the flux ordinarily striking the photometer disk, another

beam coming from the lamp at a different angle is reflected into the photometer. The angle should be such that if the lamp is held stationary and the candlepower along the photometric axis is a maximum, the mirror is placed so that a beam in the direction from the source where the candlepower is a minimum is reflected into the photometer. Thus an average is approached and the flickering effect reduced.

Speed. — For carbon lamps, it was early established that the mean horizontal candlepower is not altered by revolving the lamp, so long as the speed of revolution is not so great as to cause the filament to bend out so as to touch the side of the bulb. Ordinary vacuum tungsten lamps can be rotated at a speed such that the filament does not bulge out, 100 r. p. m. being common practice. At faster speeds the filament may break. But with the introduction of the gas-filled tungsten lamp, it was found that these conditions no longer held. The candlepower for such lamps varies with the speed of rotation. Time will not be taken to discuss the reasons for this or the experimental data but at the Bureau of Standards, experiments showed that if a gas-filled tungsten lamp was rotated at a speed such that the current was the same as when the lamp was stationary, and if the lamp was burned in the proper position, the mean horizontal candlepower could be determined in the usual way.

Mean Spherical Candlepower — The mean spherical candlepower may be obtained in one of three ways, either by measuring the candlepower in various azimuths and zones and computing, called the "point-by-point" method; by computation from the mean horizontal candlepower using the reduction factor; or by a single measurement with auxiliary apparatus such as a mean spherical photometer, holophotometer, lumen-meter, or an "Ulbricht" integrating sphere.

Computation. — By definition, the mean spherical candlepower is the total flux divided by the total solid angle. To compute the total flux, let it be assumed that the average candlepower, I_θ, at any angle, θ, measured from the vertical is known. The area of an infinitesimal zone at that elevation will be $2\pi r^2 \sin\theta\, d\theta$. The illumination of an infinitesimal area of this zone will be $\frac{I_\theta}{r^2}$; the flux, therefore, will be $\frac{2\pi r^2 I_\theta \sin\theta\, d\theta}{r^2}$, the total flux will be $2\pi \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} I_\theta \sin\theta\, d\theta$, and the mean spherical candlepower will be this divided by 4π or $\frac{1}{2}\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} I_\theta \sin\theta\, d\theta$ where I_θ is the *average* luminous intensity or mean candlepower at the angle θ obtained by the point-by-point method, either by measurement

with the lamp rotating, or by a series of measurements around the lamp as in the case of the mean horizontal candlepower. Taking a vertical plane through the axis of the lamp, the distribution curve of the source may be plotted in polar coördinates. If the equation of this curve were known, a substitution for I_θ of its value as a function of θ would make possible a determination of the mean spherical candlepower. Such an integration might or might not be complicated.

Middle-Zone Method. — A simple procedure is as follows: Divide the sphere into n equiangular zones. Then, in any given zone, there is some angle at which the product $I_\theta \sin\theta$ is the same as the average over the zone. The flux in that zone, say the first above the horizontal, can then be written as

$$F_{\theta_1} = 2\pi I_{\theta_1} \sin\theta_1 \int_0^{\frac{\pi}{n}} d\theta = \frac{2\pi^2}{n} I_{\theta_1} \sin\theta_1$$

where θ_1 is the angle at which the candlepower is such that $I_{\theta_1} \sin\theta_1$ is the average of that product throughout the zone. Then the total flux would be $\frac{2\pi^2}{n} \sum I_\theta \sin\theta$ and the mean spherical candlepower would be

$$\frac{1}{4\pi} \times \text{total flux or } \frac{\pi}{2n} \sum I_\theta \sin\theta.$$

It is found that if θ is taken at the *middle* of the zone and if 18 zones are used, i.e., every 10 degrees above and below the horizontal, the result will be correct for all distributions ordinarily encountered to within less than 0.5 per cent. If a measurement is made at the same time of the mean horizontal candlepower, the ratio of the mean spherical to the mean horizontal will give the reduction factor. Any subsequent measurements of the m. h. cp. will enable a computation of the m. sph. cp., in case the m. h. changes. This is one of the quickest methods of obtaining the m. sph. cp., but quite a number of other methods have been suggested to compute the m. sph. cp. when the candlepower has been measured at sufficient angles to give the distribution curve. The most common of these methods is known as the Rousseau method.

Universal Rotator and Mirror Systems. — To measure the candlepower at various angles, two modes of procedure are in general use. If the source, either a lamp or a lamp and reflector, can be rotated, it may be mounted in the socket of what is called a universal rotator which, while the lamp is rotating about an axis in one plane, enables it to be set at various angles in a plane perpendicular to the first. If the source cannot be rotated, a system of mirrors is used. In this case, care must be exercised to see that the mirrors are as uniform in reflecting power as possible and that they are thoroughly cleaned.

Radial Photometer. — A third method of getting distribution curves uses what is called a "radial" photometer. In this case, the source to be measured is raised and lowered along a vertical line. It is connected by means of a fixed arm to the photometer-head in such a way that the latter is turned about a horizontal axis so that the angle of incidence on one side of the screen is the same as that on the other for every position of the lamp to be measured.

A number of integrating photometers have been devised, the purpose of which is to give the mean spherical or mean hemispherical candle-power with one reading. The most prominent of such instruments are the Mathews integrating photometer, the Blondel lumen-meter, and the Ulbricht integrating sphere.

Mathews Photometer. — The Mathews instrument for measuring incandescent lamps consists of a series of mirrors arranged around a

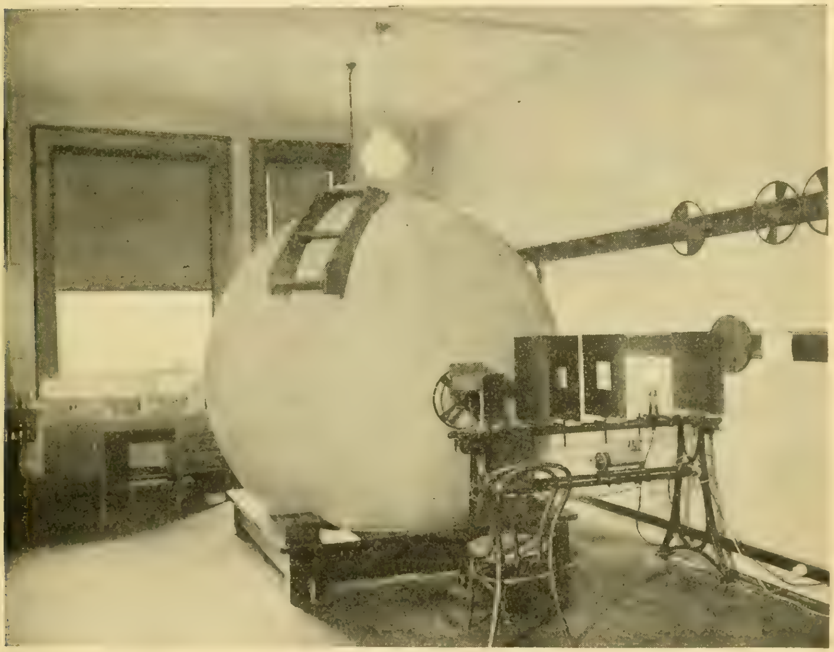


FIG. 77. Ulbricht Sphere.

semi-circular frame, so that in any zone the mirror corresponding to that zone is placed at an angle such that $I_\theta \cos \theta$ is the average for the zone. This and the Blondel instrument are expensive to make and have been generally superseded by the Ulbricht sphere.

Ulbricht Sphere. — The Ulbricht sphere, Fig. 77, has now come into use in factories as a result of the necessity for an integrating instrument

for the measurement of gas-filled tungsten lamps. It consists of a large hollow sphere coated on its inner surface with a white paint or other material of as nearly perfect diffusing power as possible, and having at one point a small window of translucent glass set into it. The lamp to be measured is placed inside of the sphere, and between it and the window is placed a white screen so that the direct rays from the lamp do not strike the window. Then the brightness of the window is directly proportional to the mean spherical candlepower of the source.

Theory of the Sphere. — The proof of this principle may be derived as follows (Fig. 78): The illumination on any infinitesimal element of the sphere, such as da at A, will be due to direct light from L, to light from every point such as B, due to light from L once reflected; to light from every point such as C, due to light from L twice reflected, etc. The direct illumination will be a function of the candlepower of L in the direction LA and the distance. Call this E_{LA}. Any point, B, receives light directly from L and reflects it to A, and hence B may be considered a secondary source. Let E_B be the illumination on any infinitesimal part of the surface db at B due to direct light. Then E_Bk will be the brightness in lamberts and $\frac{E_Bk}{\pi}$, the brightness in candles per sq. cm. The candlepower of db in the direction A will be $\frac{E_Bk}{\pi} \cos\theta \, db = \frac{dF_Bk}{\pi} \cos\theta$, where dF_B is the flux incident on db. The illumination at A will be $\frac{dF_Bk \cos\theta \cos\theta}{\pi l^2} = \frac{dF_Bk \cos^2\theta}{4\pi r^2 \cos^2\theta} = \frac{dF_Bk}{4\pi r^2}$, since $\frac{l}{2} = r\cos\theta$.

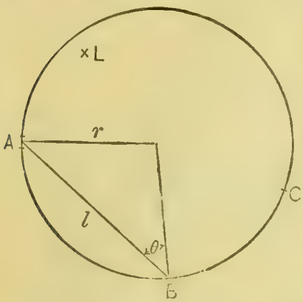


Fig. 78. Diagram for Computation of Theory of Ulbricht Sphere.

∴ total illumination on da due to all light once reflected will be

$$\sum \frac{dF_Bk}{4\pi r^2} = F_c \frac{k}{S} \text{ where } F_c \text{ is the total flux from } L.$$

This would also be the total illumination on an infinitesimal element, dc, at C due to light once reflected. To get the illumination on da due to light from dc, which has been twice reflected, take as before the brightness in candles per sq. cm. of $dc = \frac{E_ck}{\pi}$ where E_c is $F_c\frac{k}{S}$ and the

candlepower in the direction, $da = \frac{E_c k}{\pi} \cos \beta \, dc$. $\therefore$ Illumination $E_c A$ $= \frac{E_c k \cos \beta \, dc \cos \beta}{\pi \, 4r^2 \cos^2 \beta} = \frac{E_c k \, dc}{4\pi r^2} = \frac{F_c k}{S} k \frac{dc}{S}$.

$\therefore$ Total illumination at da due to light twice reflected $= \sum F_c \frac{k}{S} k \frac{dc}{S} = F_c \frac{k^2}{S}$. Continuing this procedure, the total illumination on da will be equal to

$$E_{(LA)} + \frac{F_c}{S} \sum k + k^2 + k^3 + \cdot \cdot \cdot = E_{(LA)} + \frac{F_c k}{S} \left(\frac{1}{1 - k} \right).$$

If then da is shielded from the direct light from L, thereby eliminating the term, $E_{(LA)}$, the remaining illumination will be proportional to $\frac{F_c}{S}$. But this is proportional to the mean spherical candlepower. Hence, the illumination on the small window is proportional to the mean spherical candlepower provided it is shielded from the direct rays from the source.

Errors. — The above theory applies rigorously to a perfectly diffusing surface and an empty sphere, and the presence of the source with its fittings and the screen to cut off the direct light evidently constitute variations from the ideal conditions. Other variations lie in the imperfect diffusing character of the surface and in the presence of the window whose surface is a translucent milk-glass. It is beyond the scope of this work to go into a discussion of these various sources of error. It is sufficient to point out here that some of the errors can be minimized by using the "substitution" method of measurement, and this method should be used exclusively. Furthermore, where a large source, such as a lamp and reflector or an arc lamp, is to be measured, both the standard and the unknown source should be kept in the sphere, so that absorption by the lamp parts will be allowed for when readings are being taken on the standard. The position of the source in the sphere is immaterial as long as it is not too close to the sphere wall. The screen used to shut off direct light from the window should be as small as possible and about $0.4r$ distant from the lamp, where r is the radius of the sphere. Obviously, if the unknown and the standard are both in the sphere, two screens must be used, and in this case it is common to place a third screen between the two sources. Experience has shown that the screens used should be opaque. White blotting paper makes a very good screen material.

Photometer for Sphere. — In using the sphere the brightness of the translucent window is compared with a surface whose brightness can

be varied in a known way. Thus an illuminometer can be used as a photometer and pointed at the window. Then a standard whose mean spherical candlepower has been determined by the point-by-point method is placed in the sphere and, the voltage of the comparison lamp having been adjusted for color-match, the scale reading for brightness match is noted. If the scale is properly calibrated, the mean spherical candlepower of an unknown source substituted for the standard can be determined by direct proportionality.

By placing a mirror in one side of the Lummer and Brodhun photometer-head so as to reflect into the cube the light coming from the window and shutting off the light from that side of the disk, measurements may be made in the usual way by keeping the photometer stationary and moving the comparison lamp. The mean spherical candlepower of two sources will then vary inversely as the square of the corresponding comparison lamp distances for balance.

Paint. — One of the early difficulties with the sphere was the finding of a suitable material to coat the interior. Such a material should have as high a diffuse reflecting power as possible and should be non-selective in its absorption, i.e., as white as possible. Furthermore, it should not change with age. The effect of dust and dirt is obvious, and frequent recoating seems necessary where accuracy is important, although the substitution method of measurement tends to minimize these errors. Recently a paint has been devised especially for this purpose, and for cases where a similar necessity occurs, which gives promise of solving the difficulty. Spheres have been constructed in a number of different sizes, but the larger the sphere, the smaller the errors due to screens, etc.

The sphere has found quite wide application in the photometry of arc lamps where the intensity in a given direction is constantly changing. Recently, since the introduction of the gas-filled tungsten lamp, it has come into general use in the photometry of these lamps. It has also been adapted for use in measuring reflection factors.

Brightness Measurement. — Besides the measurement of candlepower, photometry is concerned with the measurement of illumination and brightness. The method of measuring the former was outlined in the description of the Weber photometer. To measure the brightness of a self-luminous source, such as an incandescent lamp filament, its intensity in a direction normal to the filament is measured. This divided by the projected area will give the brightness. If the brightness of a wall or other reflecting luminous surface is to be measured, the illuminometer is usually employed, and, arranged as a photometer, has its tube pointed at the wall in question. In this case, the scale must be calibrated in brightness units and this is done by using an auxiliary white

diffusing surface whose coefficient of diffuse reflection is known and illuminating it by a source of known candlepower placed at a known distance.

Measurement of Reflector Units. — The measurement of lamps with reflectors involves a number of variations in the ordinary photometric procedure. In the first place, the sources are in general quite large and, furthermore, the light flux is more or less controlled in its direction and hence the inverse square law must be applied with reservations. Such sources may be divided into two broad classes, those used for general interior and exterior illumination, as in stores, factories, streets, etc., and those used for projection purposes, such as automobile headlights, searchlights, floodlights, motion-picture work, etc. For sources of the first class, it has become accepted practice, where possible, to place the photometer at a distance of 10 feet from the lamp and reflector and make adjustments for a balance by moving the comparison lamp. For sources of the second class having a parabolic reflector, measurements are made at a distance greater than that at which the beam has ceased to be divergent and become convergent. For floodlighting projectors, this distance seldom needs to be more than 25 feet. For large searchlights, it may run from 1000 to 2000 feet.

Apparent Candlepower. — Sources of the first class are usually measured with an ordinary photometer for their distribution curve, or in a sphere, in order to determine the total flux. Recently, the sphere has also been adapted for the measurement of searchlight beams and floodlighting units, but it has been more common practice to determine the candlepower at various points across the beam, using a photometer of the portable type. The resulting candlepower is sometimes called the "apparent" candlepower by which is meant the luminous intensity which a standard lamp would have to have to produce at the given distance and in the given direction the illumination measured. While the practice has not yet been standardized, in most cases the distance is measured to the center of the filament as the center of radiation.

Color Photometry and Objective or Physical Photometry

It has so far been assumed that the lights to be measured were either of the same color or else so nearly the same as not to cause inconvenience or uncertainty in making settings. But the continual tendency in incandescent lamps toward a light which is relatively stronger in the blue radiations has made the question of heterochromatic or color photometry increasingly important, and it has long been a factor in the

measurement of arc lamps and incandescent gas mantles. In determining the candlepower of a tungsten lamp in terms of a carbon lamp standard, it is found necessary to make a comparison of a red-colored field with a blue-colored field.

When the parts of the photometer field appear different in color, the eye is confronted with the comparison not only of brightness but of color difference, and it is more difficult to decide when the parts of the field are equally bright or have equal contrast than under conditions of equality of color. The difficulty increases as the color difference is larger. It is harder to remember the criterion from lamp to lamp, and different observers get different results. A phenomenon called the "Purkinje effect" is also a factor and must be considered where weak illuminations are encountered. In such cases, i.e., weak illumination, the eye is more sensitive to blue than to red light, and this may be taken as a condensed statement of the Purkinje effect.

However, within certain limits of error, which widen as the color difference increases, it is possible to form a judgment as to when two fields illuminated by lights of different tint appear equally bright and the ordinary forms of photometer can be used for the purpose. Some observers claim the simple equality or match type is preferable to the contrast type, but this seems to be a matter of habit and preference, just as some observers prefer the Bunsen Leeson-disk photometer to the Lummer and Brodhun.

Flicker Photometer

A type of instrument which has come increasingly into prominence in the past few years is the so-called "flicker" photometer, which has been evolved from the work of Rood. He discovered that when

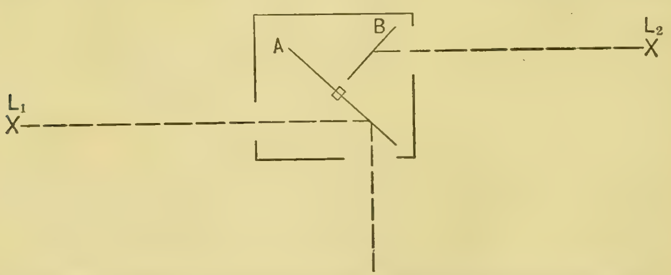


Fig. 79. Diagrammatic Sketch of Whitman Flicker Photometer.

two colored surfaces are alternately presented to view in rapid succession, the sensation of color disappears, or the color sensations of the two are mingled, although a sensation of flicker may still persist. More-

over, there is a condition of illumination of two such surfaces when the flicker tends to disappear. It is then assumed that the illumination is the same on both surfaces, but this is only an assumption. Various photometers on this principle have been built. The essential requirement is a revolving device which shall present to the eye in succession fields illuminated by the two sources.

Whitman's Photometer. — One of the simplest and earliest forms is that due to Whitman (Fig. 79). Let A be a rotating sector whose solid portions on the side toward L_1 have a white diffusing surface. Let B be a stationary surface of the same material. Then the eye will see a surface illuminated by L_1 when a solid sector of A is in front of the eyepiece; and then as A revolves and an open sector comes in the line of sight, B will be seen illuminated by L_2.

Rotating-prism Type. — A common type of instrument is one in which a rotating prism is used to produce the alternations in the field. Figure 80 shows such an instrument. Recently there has been made available an attachment containing a rotating prism which can be applied to an ordinary Lummer and Brodhun photometer to make it into a flicker instrument.

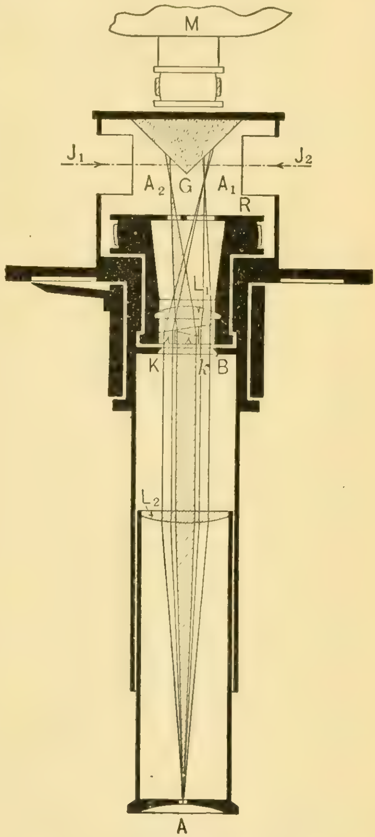


Fig. 80. Rotating-Prism Type of Flicker Photometer.

M — Motor.
G — Photometer screen.
R — Rotating holder for lens L_1 and double wedge prism K.
L_2 — Eye-piece lens.

When this attachment is used, the contrast absorption strips of the photometer must be removed; otherwise, there will always be an outstanding intensity flicker.

As a result of the latest work on this subject, the following are given as the requirements of a satisfactory flicker photometer:

Requirements. — *First,* undue tiring of the eyes should be guarded against. This is secured mainly by making the surroundings of the flickering field light instead of dark. The intensity of the illumination

for this purpose should be equal to, or less than, the intensity of the comparison field. If brighter, it attracts the attention. The intensity and color of this surrounding field do not seem to influence the accuracy, at least within wide limits. It should be illuminated uniformly and should be free from mechanical defects.

Second, there should be no mechanical flicker in the comparison field itself. This is secured by keeping the optical system clean and so adjusting it that its focus is in space and not on a surface. The focus of the eye-piece lens, of course, should be on the plane of the opening through the external field just referred to.

Third, in securing a balance, the color flicker (as distinguished from the intensity flicker) should be reduced to a minimum by a proper regulation of the speed of alternation of the colors.

Sensitivity. — Evidently the sensitiveness of this kind of photometric apparatus is a function of the speed of flicker, as with too high a speed the flicker will disappear before the so-called equality-of-illumination condition is reached, and at too low a speed the flicker will not disappear at all. The disk, therefore, should be rotated at the maximum speed at which flicker disappears. This speed is a function of the degree of illumination. It may also depend on the observer.

It has not yet been definitely accepted by photometrists that the cessation of flicker indicates equality of brightness or some other condition. But experiments are still being carried on to test this, and the latest evidence seems to show that the flicker photometer is a fairly satisfactory instrument where sources with color differences comprised in the range of ordinary incandescent lamps must be measured and where the illumination on the photometer disk is fairly high. If spectral colors are to be compared, say a red and a green, results with the flicker photometer differ from those with a direct comparison method very materially and this problem is still unsettled.

Aside from the theoretical objections to the flicker photometer, the use of the instrument is somewhat fatiguing to the eye. Its great advantage lies in the method of handling the color difficulty.

It is much better, however, to work with conditions of color match. To this end a number of methods have been and are used to make possible the avoidance of color difference by jumping the gap once for all. Thus, if the standards are carbon lamps and it is desired to measure tungsten lamps, some method should be used to calibrate tungsten-lamp standards and thereafter use them in place of the carbon lamps. If arc lamps are to be measured in terms of incandescent-lamp standards, some method should be found by which the color of the standard

can be altered in a known manner so that the resultant light matches the arc lamp in color.

Crova Method

Crova suggested an ingenious scheme which is known as the "Crova method." If two sources differ in color, then the curves showing the relative candlepower at different wave-lengths in the visible spectrum will differ but there will be *some wave-length* at which the ratio of candlepowers will be the same as the ratio of the candlepowers of the sources taken as a whole. If, then, an absorbing screen is placed in the eye-piece of the photometer which transmits light only of that wave-length, the photometric comparison of the two sources can be carried on as in the case of the ordinary sources not differing in color.

Theoretically, such an absorbing screen would give correct results only for sources whose spectral character was exactly like the first two. But it has been found experimentally that over ranges encountered in ordinary incandescent lamp work, such as the comparison of vacuum tungsten lamps against carbon lamps, this method can be used without appreciable error and has been used in at least one large factory. A screen which transmits as little light as possible of wave-lengths other than 0.58 should be chosen for the range mentioned.

An extension of this method, involving successive measurements through two screens, one a red glass, the other a green glass, has also been used.

Blue Glass. — If measurements are made of a tungsten lamp against a carbon lamp, it is possible to find a glass of bluish tint which can be placed on the carbon-lamp side of the photometer-head and so alter the character of the light reaching the screen that it matches very closely in color the light from the tungsten lamp. This blue glass screen can be calibrated once for all to determine its transmission and can then be used to cover the color range for which it is designed. A series of such glasses of proper tint can be calibrated so that measurements against a carbon standard can be made with vacuum or gas-filled tungsten lamps or arc lamps. A recent extension of this idea is the use of colored filters containing solutions whose color can be changed so as to take care of any color difference ordinarily encountered in the measurement of incandescent lamps.

Filter for Incandescent Lamps. — A typical solution is as follows:

Nickel ammonium sulphate	50 gms.
Ammonium sulphate	10 gms.
Ammonia (0.90 gravity)	55 cc.
Water to	1 liter of solution

Dilute with water containing 10 gms. of ammonium sulphate per liter.

The solution should be used as fresh as possible because on standing it dissolves the glass of the containing vessel. Various concentrations of this solution in the proper kind of flat and parallel-walled glass receptacle will give a color match between a carbon lamp and a tungsten lamp throughout the range from 3.5 down to about 0.4 watts per mean hemispherical candlepower. Various precautions must be used in connection with the employment of such filters.

The problem of color photometry is by no means settled. The nicest solution, if it were feasible, would be to have the question confined to the Bureau of Standards and have the Bureau furnish standard lamps of the desired color. But at the present time, so many standards would be required that the cost would be almost prohibitive.

Spectrophotometry. — An entirely different branch of photometric work involves the determination of the relative radiant flux of various wave-lengths in the visible spectrum of a source. Here the spectrophotometer plays a rôle in the visible region similar to that of the radiometer or other energy-measuring instrument in the infra-red or ultra-violet parts of the spectrum. What is done is to compare, in a photometric field, light of one wave-length (generally, in practice, of an extremely narrow region of the spectrum) from one source with that from a standard source, continuing this for all wave-lengths throughout the visible. The result *for any given wave-length* is a ratio of the luminous intensity of the one source to that of the other for the particular wave-length. But this is also the ratio of the radiant flux of this particular wave-length of the one source to that of the other, since the visibility, K_λ, drops out.

The results are plotted in the form of a curve with ratios as ordinates and wave-lengths as abscissas. The distribution of radiant flux of the standard source is known, and if it is plotted and the values at the various wave-lengths multiplied by the ratios as derived from the other curve, a third curve, the distribution curve of the unknown source, showing the relative radiant flux, will be obtained.

It should be emphasized that this use of the instrument gives only relative results. It is not as yet possible to measure the actual candlepower of the luminous flux of a particular wave-length, because no unit of candlepower in red light, for instance, exists. Moreover, there is no accepted unit of candlepower in green light or blue light. In other words, while the pentane lamp is accepted as a standard for maintaining the unit of integral or white light, as it is called, the intensity of the pentane in the red is not accepted as a standard for red light. Furthermore, if one were to try to measure a red light against the integral light of the pentane, there is no generally accepted method,

no standardized method, by which to carry out the measurement. However, the spectrophotometer does give an idea of the quality of light and provides the most analytical method for determining this factor. This method should not be confused with the methods used in colorimeters, which will be discussed elsewhere.

Physical Photometers. — Many attempts have been made to find photometric methods which would give results without making the eye the measuring instrument. Of course, the eye is the ultimate judge, but there is no reason why most of the work should not be done by mechanical means, leaving the standardizing to the regular photometers using the eye.

Radiometer. — The first thing which would naturally suggest itself in the search for a so-called physical photometer is some form of radiant-flux-measuring instrument, such as a radiometer, or bolometer, since what is to be measured is associated with radiant energy. But the trouble with the radiometer is that it does not differentiate between radiant flux manifested in green light, for instance, and the same amount of flux radiated in red. Suppose it were possible, however, to make a filter or other absorbing device which could be inserted in the path of the light beam and which would act on each wave-length so as to reduce its intensity to such an extent that it had the same relative value compared to that of other wave-lengths as it has in a luminous way in affecting the eye. In other words, considering the energy curve of the source in the visible and the visibility curve, what is needed is a filter which will act on the various wave-lengths so as to produce the same relative effect on the transmitted flux as would be obtained if these two curves were multiplied together. Several investigators have claimed to produce such filters, but they are not yet used outside of the laboratory. One of the difficulties of such an arrangement, i.e., a radiometer and filter, is the small amount of energy available for measurement in the ordinary source.

Selenium. — A promising field of research lies in an entirely different direction. For a number of years it has been known that selenium changes its electrical resistance when exposed to light, and many attempts to utilize this phenomenon in photometry have been made.

Selenium occurs in the gray and red crystalline form, the gray being light-sensitive. It is mounted in a thin layer on insulating material in an evacuated bulb so that the surface is protected from the effect of gases in the air. Such an arrangement is called a selenium cell. It is connected up in an arm of a Wheatstone bridge or used in conjunction with a potentiometer. A high-resistance over-damped galvanometer is used to measure the change in resistance, the latter being high in the

dark and low in the light. Unfortunately, the relation between the candlepower of the light and the change of resistance is very complicated and is a function of the candlepower. Furthermore, the sensitivity of the cell for light of various wave-lengths is not uniform and the curve is not the same as the visibility curve of the eye. Hence, the cell is not satisfactory for use in ordinary photometric work. It can, however, be used for certain classes of monochromatic comparisons, such as the comparison of a green and a red, in which case the sensitivity curve of the cell must be known. The cell is sensitive through a region extending from 0.900μ to less than 0.250μ in the ultra-violet, and can be used to measure the transparency and reflectivity of glasses and mirrors throughout this range.

Photo-electric Cell. — Of late years, the photo-electric cell has come increasingly into prominence as a photometric instrument. It is based on the principle that the alkali metals are the most sensitive of the metals to a phenomenon known as the "photo-electric effect." The alkali, sodium or potassium for instance, is put in an evacuated bulb which contains a platinum ring, and the alkali and the ring are connected to wires sealed into the bulb so that they can be used as electrodes. The platinum is connected to the positive side of a battery having a voltage of 300, for instance. The negative side of the battery is connected to earth. The alkali is also connected to earth. Then there exists a difference of potential in the cell of 300 volts. If, now, the alkali is illuminated, it will be found that a small current flows in the wire connecting the alkali to the earth. The action is electronic and no attempt will be made to go into the theory. The current is quite small but can be detected by a galvanometer if the candlepower is that of ordinary illuminants and the cell has a large area and the applied voltage is sufficient. If the alkali circuit contains a very high resistance, 10 or 100 megohms, for instance, and an electrometer is used to measure the drop across this resistance, the cell is sensitive to very small quantities of light, approaching those detectable by the eye. This cell is already being used in astronomical photometry.

The sensitivity to different wave-lengths is not the same, and the cell has a sensitivity curve with a maximum out in the violet end of the spectrum. Hence, if used in work where there is a color difference, an absorbing cell with a transmission like the visibility curve of the eye would have to be used. A question equally important, if not more so, is the relation between the intensity of illumination and the current in the alkali circuit. Considerable work has been done recently on this relationship. For small ranges of illumination, cells can be made for which this relationship is linear; but for large ranges some question

still exists. In general, it may be said that physical photometry is still in an experimental stage.

PROBLEMS IN PHOTOMETRY

1. A photometer bench is 2 meters long. At one end is a lamp having a candlepower of 15 in the direction of the photometer. At the other end is a lamp having a candlepower of 30. How far from the first lamp must the photometer be placed to have the same illumination from both lamps?

2. A photometer bench scale is 200 cm. between the lamp holders. If the 40 candlepower point on the scale comes at 120 cm. from the left-hand holder, how far from this holder will the 20 candlepower point be? The 60 candlepower point?

3. A photometer bar is 250 cm. between fixed light sources. The center of the scale is marked 25 candlepower. Show how to compute the positions of other candlepower points so as to make the rest of the scale read directly in candlepower.

4. What is the total luminous flux from a hefner lamp, assuming its candlepower to be uniform in all directions?

5. A lamp and reflector show an average candlepower of 100 throughout a zone comprised between 25° and 35° from the vertical. What is the flux in lumens in this zone?

6. An arc lamp is 50 feet from the center of a window in a house. The luminous flux from the arc makes an angle of 60° with the plane of the window, which has an area of 5 sq. ft. The arc has a uniform candlepower of 500 candles in all directions intercepted by the window.

(*a*) What is the average illumination on the window in foot-candles?

(*b*) What is the luminous flux in lumens incident on the window?

7. The surface of a desk makes an angle of 30° with the direction in which a lamp, located 3 meters away, has a candlepower of 25. What is the illumination on the desk at a point corresponding to the given direction in lux and foot-candles?

8. What is the candlepower of a 200-watt lamp operating at 0.9 w.p.c. in the direction at which an illuminometer, whose disk is 6 feet away, shows a scale reading of 5 foot-candles.

9. In the use of lamps surrounded by globes, the maximum globe-surface brightness allowable to avoid glare may be taken as 0.5 candles per sq. cm. If the transmission factor of a spherical enclosing shade 13 cm. in diameter is 0.85, what is the lowest permissible mean horizontal candlepower of a tungsten lamp to be used inside this shade when the reduction factor of the lamp is 0.8?

NOTE. — To solve this problem, reduce to lamberts and then back to candlepower.

10. A lamp 2 meters away has 200 candlepower in a direction making an angle of 60° with the vertical from a picture. If the reflection factor of the painting is 20 per cent in a direction 30° from the normal, what is the brightness of the painting in that direction in millilamberts? What is the brightness of the glass covering the painting if its reflection factor in that direction is 10 per cent?

11. A piece of white blotting paper has a reflection factor of 0.8. In using it to calibrate an illuminometer, it is set 100 cm. from a standard lamp the candlepower of which in the direction normal to the paper is 20. What will be the brightness in millilamberts in any direction within the zone 45° above and below the normal, where perfect diffusion may be assumed? What will be the brightness in candles per sq. cm. within the same zone?

12. The lamp of a street light is 10 feet from the ground. What is the brightness of a spot on the pavement when viewed at an angle of 30° from the normal, at a distance of 100 feet from the base of the lamp post, the candlepower in the direction of the spot being 200, and the reflection factor of the pavement being 0.2, assuming perfect diffusion?

NOTE. — Reduce from foot-candles to milliphots and get millilamberts.

COLLATERAL READING

Photometry

PALAZ, A., A Treatise on Industrial Photometry, translated by Patterson (D. Van Nostrand, New York, 1896).

TROTTER, A. P., Illumination, Its Distribution and Measurement (MacMillan & Co., Ltd., London, 1911).

BOND, C. O., Working Standards of Light and Their Use in the Photometry of Gas, J. Frank. Inst., **27,** 189 (1908).

MILLAR, P. S., Illumination Photometers and Their Use, Trans. I. E. S., **2,** 546 (1907).

ROSA, E. B, and TAYLOR, A. H., The Integrating Sphere: Its Construction and Use, Trans. I. E. S., **11,** 453 (1916).

IVES, H. E., The Establishment of Photometry on a Physical Basis, J. Frank. Inst., **180,** 409 (1915).

CRITTENDEN, E. C., and RICHTMEYER, F. K., The Precision of Photometric Measurements, J. Optical Soc. Am., **4,** 371 (1920).

CHAPTER IV

PHYSIOLOGICAL OPTICS

[P. W. COBB]

General Structure of the Eye

The eye as an optical instrument is not essentially different from a photographic camera. The eyeball is nearly spherical (Fig. 81) and its walls are composed of three layers or coats: (1) The outer coat, called the **sclera,** is fibrous in character and is the supporting structure of the

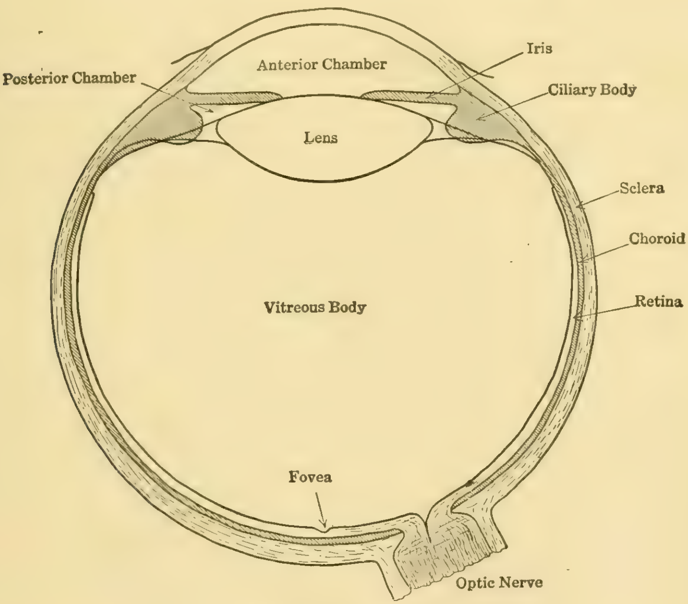


FIG. 81. General Structure of the Eyeball.

eyeball. Its visible portion, in front, is known as the "white of the eye." At the forward pole of the eyeball it becomes clear, and has a shorter radius of curvature than elsewhere. This portion of the outer coat is called the **cornea,** and is the first refracting surface of the dioptric system. (2) The choroid coat is composed chiefly of blood vessels, and lies just within the sclera, separating it from (3) the **retina,** the sensitive

surface which receives the light-impression, and which is composed principally of three sets of nerve-cells with their fibres, connecting with the brain through the optic nerve.

The **lens** supplements the cornea in the refractive system, and is an elastic, transparent body, contained between two thin, fibrous layers known as the lens-capsule. Under the action of a ring-shaped muscle, the **ciliary muscle,** the tension on the capsule is altered, and the result is an increase in curvature of the front surface of the lens, by which the eye is focused or *accommodated* for nearer objects. The **iris** is the diaphragm of the eye, and lies touching the front layer of the lens-capsule. Both iris and ciliary muscle are to be looked upon as specialized portions of the choroid.

Refractive Apparatus of the Eye

The spaces within the eyeball are all filled. The anterior and posterior chambers, between the cornea and the lens-capsule, and separated by the iris, are filled with a watery substance, known as the **aqueous** (or aqueous humor, in the older terminology). The remainder of the eyeball, its chief bulk, is filled with a transparent, jelly-like material known as the **vitreous,** the vitreous body, or the vitreous humor. These media have a refractive index, 1.336, very nearly that of water.

Refraction takes place in the eye at three surfaces: at the cornea, and at the anterior and posterior lens-surfaces. As the cornea is of uniform thickness it does not, of itself, significantly modify the course of light passing through it, and the refraction at its surface is taken as that due to a surface of the aqueous of equal curvature. Thus, while the cornea has an index of 1.377, its effective index is 1.336.

The lens is not uniform in its refractive index, but is denser at the center and less dense in its superficial portions. A homogeneous lens of the same dimensions and optical properties would have an idex of refraction of 1.437. It must be remembered that the lens is "immersed" in media having a refractive index of 1.336, and that its refraction is thereby correspondingly reduced.

The dioptric system of the eye is then defined by the following average dimensions:

Refracting Surfaces

	Radius of Curvature	*Refractive Index*
Cornea	7.8 mm.	1.377 (equivalent 1.336)
Aqueous		1.336
Lens, anterior surface	10.0 mm.	1.437 (immersed)
Lens, posterior surface	6.0 mm.	

In accommodation for near objects, the radii of curvature of the anterior and posterior surfaces of the lens change to 6.0 and 5.5 mm., respectively.

Distances	*Interval*	*From Cornea*
Cornea to anterior lens surface. . .	3.6 mm.	3.6 mm.
Cornea to posterior lens surface. .	3.6 mm.	7.2 mm.
Cornea to retina.	14.6 mm.	21.8 mm.

The size of the image on the retina may be computed in any case by a simple proportion, if the distance of the object, d, and any dimension, a, of the object, projected on a plane normal to the line of sight, are known. The corresponding dimension, x, in the image is given by the proportion:

$$d : a = 15.5 \text{ mm.} : x.$$

Adjustments of the Eyes

There are compensations which make the best of the optical defects of the eye. Accommodation, brought about by the ciliary muscle, has already been mentioned. The eye comes quickly to the adjustment of sharpest focus for the object looked at. The pupil contracts somewhat with the change from far to near in accommodation. It is not quite clear what purpose this contraction serves. In general, reducing the size of the light-pencil tends to reduce the adverse effect of the various refractive errors. Further, the pupil reacts quickly to an increase in light, by contracting in size, and conversely by dilating in dim light; it thus protects the eye from sudden flooding with light, and permits the entrance of more light where the illumination is so low and vision is in consequence so dim that the refractive errors are of small relative importance. Maximum dilatation takes place slowly in very dim light or in the dark, and is slowly regained after a flash of light. Over a wide range of light-intensities, the pupil will in a short time resume its so-called physiological size of 3 to 4 mm. diameter, when the light is kept constant, and the change in the size of the pupil is consequently transient and only a partial explanation of the power of the eye to adapt itself to various brightnesses.

The most striking and important adjustments of the two eyes, which go far to offset their optical defects, are those which result from their rapid and accurate shifts in direction. The two eyes, taken together, perform these turning movements every time there is a shift in vision from one object to another. The axes of the eyes then shift so as to intersect at the new fixation point, be it near or far, and what-

ever its direction from the person seeing. These movements are brought about by two sets of six small muscles each. These muscles are attached to the eyeball (Fig. 82) and are housed within the bony eye-socket or **orbit.** They are incessantly active during waking hours, perhaps more active than any other muscles of the body, except the heart. The nerves which supply them with impulses to contraction are much larger in proportion than for any of the other body muscles. It requires only a moment's thought to see what accurate coördination is required of these muscles and the nerve centers which control them, and what an enormous amount of activity they go through in the course of the day's work. Indeed, the failure of these muscles and nerves to function properly is the basis of a large and important chapter in ophthalmology.

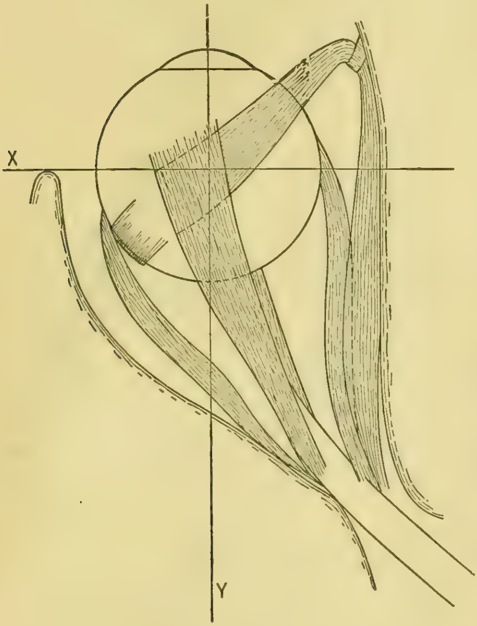


Fig. 82. Extrinsic Muscles of the Eye.

The lighting engineer will do well to think of the eyes as almost continually in motion. Experimental study has made it appear that the stops or pauses (fixations) of the eyes in rapid work last only a small fraction of a second. Thus it becomes important that the lighting shall be such as to make possible an effective impression upon the retina in a very short time. Otherwise the impression will be inadequate, the eye-muscles will have extra work thrown upon them and become more rapidly exhausted, the work will be slow, and mistakes will be frequent.

The Structure of the Retina

The retina is a part of the nervous system, and its structure must be studied as such. This study will not be difficult if one remembers that the unit of which the nervous system is built is the **neuron,** which is a nerve-cell plus the nerve-fibers which are a part of it. Some of these fibers, the **dendrites** branch out like a tree, usually close to the

cell, and carry nervous impulses toward the cell. There is one other fiber, called the **axon** or **axite,** which is very long in some cases, and which carries impulses away from the cell, usually branching out at its extreme end. While the fibers of the neuron are continuous with its cell, communication from one neuron to another is by contact only, the terminal " brush " of one axon coming into contact with the dendrites, or with the cell body, of the next neuron in the neural path. Such a junction is called a **synapse.**

In the retina there are three sets of neurons to be considered. Beginning at the peripheral extreme (remote from the brain), the end organs which first respond to the action of light are the **rods** and the **cones** (Fig. 83, II), highly specialized endings which represent the dendrites of the first set of neurons of the retina (*B*, Fig. 83, II, III).

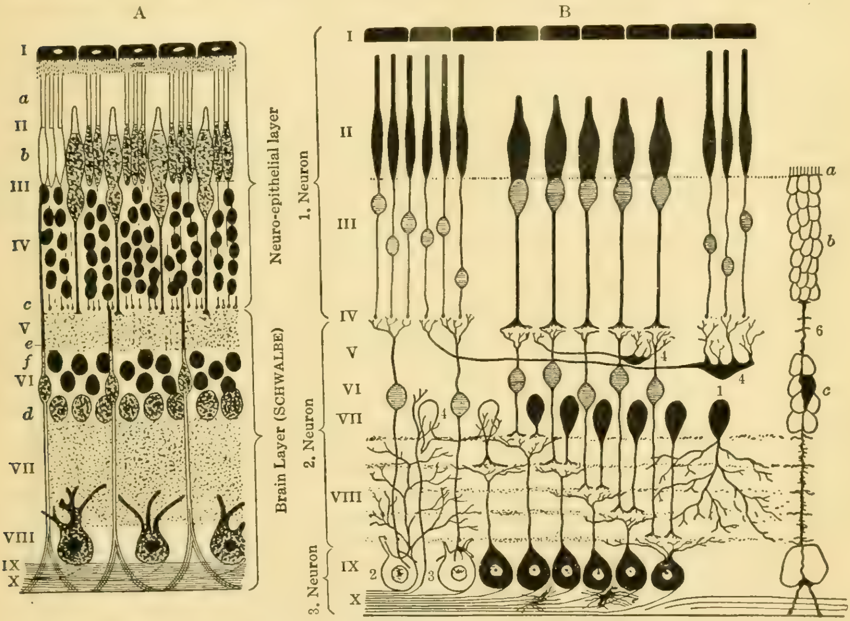


FIG. 83. Microscopic Structure of the Retina.

An intermediate set of neurons, the bipolar cells (Fig. 83), connect these with the ganglion cells (*B*, IX, Fig. 83) whose separate axons pass over the inner surface of the retina to collect at the " nerve-head " where they collectively form the optic nerve, through which the nerve impulse is finally carried to the brain. Certain other cells (*B*, Fig. 83, 4, 4) called the horizontal cells, seem to connect different parts of the same level of the retina, which appears also true of another variety of cell lying wholly within the retina, the amacrine cells (*B*, Fig. 83, 1)

which apparently have no axon but simply branch out among the synaptic connections of the second and third neurons.

It must be remembered that the retina is so disposed that the stimulating light passes directly upward in the figure, so that all the structures must be traversed by it before the sensitive rods and cones are reached.

The proportion of rods and cones varies in different parts of the retina. At the fovea, the point of direct and clearest vision, there are cones only, over an area of about 0.5 mm. diameter. Outside this the rods begin to appear, the cones becoming larger and less frequent, and the rods more numerous in the more remote portions, but no part of the retina is free from cones.

Changes in the Retina due to Light

Certain changes in these structures have been found to take place under the influence of light. There is a layer of cells containing dark pigment lying next to the layer of rods and cones (*I*, Fig. 83) which, under the influence of light, extend forward (toward the light) forming delicate pigmented partitions between the individual rods, as though to insulate them against light, one from the other. At the same time, the cones move toward the light, and away from this movement of the pigment.

Further, in the rods, there has been found a light-sensitive material known as **visual purple**. If an animal is kept in the dark for several hours and then killed, the retina, when removed, is found to have a deep purple color, and to bleach rapidly when exposed to daylight. The retina from an eye recently exposed to strong light shows no such color. By suitable means, the visual purple may be extracted from the previously darkened retina, and bleaches in solution, just as the darkened retina does, under daylight.

The Functions of the Retina. — It is quite obvious that one can see at any instant much more than the object looked at directly. The field of vision may be mapped out by having the eye fixed on a point, with the other eye well covered, and moving a small object, white or colored, to find how remote it may be from the fixation point and still be visible. In this way, it appears that a normal eye has a field of vision which is quite extensive. With one eye alone, objects may be seen about 100° outward from the fixation-point, downward 70°, inward 60° and upward 50°. Thus the two eyes have a combined field of some 200° extent horizontally and 120° vertically. The outlying portions of the field do not, it is true, afford distinct vision, but appear to be

highly sensitive to movement. Only the center has the power of interpreting fine detail. Color is not seen near the limits given — a fact which may possibly be related to the relative scarcity of the cones. Blue and yellow are recognized only over an area considerably smaller than stated. Red is seen over a still smaller area, and green has the most restricted field of all. It may in general be said that the outer portions of the retina have chiefly the function of giving notice that "something is there." One's reaction to this is to turn the eyes, and possibly the head, so as to bring the image upon the more central parts of the retina where its details and colors can be better seen.

Color-vision

The questions of the why and the how of color-vision are founded on comparatively few facts drawn from the anatomic study of the eye, and on a large number of facts elicited in the study of its functions, and have developed into an enormous amount of literature consisting largely of some scores of various color-vision theories, differing in some points but being in great measure restatements of the identical facts in different terms.

There is every reason to think that the functions of the rods and of the cones are sharply differentiated. The basis of this is the distinct difference between the behavior of vision at low and at high intensities of light. In dim light there are three things noticed: first, the eye becomes totally unable to distinguish colors; second, the very center of the retina, where there are only cones, is relatively blind under dim light; third, there is the Purkinje effect, that is, the fact that the luminosity of the spectrum is differently distributed, in that the formerly red (long-wave) rays cease to affect the eye at all, the blue (short-wave) coming to predominate, so that the brightest part of the spectrum has shifted toward the short-wave end. This is to be taken in connection with the fact that the visual purple is found in the *rods only*, and that when it is extracted from the retina, the power of the different spectral energies to bleach it is exactly in proportion to their power to excite the eye at very low intensities. Furthermore, there is a type of color-blindness in which the eye behaves exactly as the normal eye does at low intensities: it fails to differentiate color, is relatively or wholly blind at the very center of the visual field, and is sensitive to the various parts of the spectrum in the same way as the normal eye at low intensities.

These facts may be explained by the supposition that the rods are excited at light-intensities too low to excite the cones, and that the

cones are the organs which mediate all the phenomena pertaining to the color sense. In the case of the type of color-blindness referred to, it is only necessary to suppose that the cones do not function under any circumstances. This phase of the theory of vision is spoken of as the duplicity theory (*duplicitäts-theorie*) or the theory of dual function, and the form that vision takes at low intensity is called twilight vision, night vision, or **scotopic vision.** The facts of the case do not in any way contradict what is to be said of vision at high intensities, spoken of as day vision, daylight vision, or perhaps best as **photopic vision** since it takes place under artificial light as well as under daylight.

Photopic vision has several phases, among which the question of color-vision is not the least interesting. There have been for years two theories, or better, two types of theories, of color-vision extant. These may be classed as three-component theories, and as theories of antagonistic colors, respectively.

The first class is still represented by the theory of Young and Helmholtz, originated over a hundred years ago, which supposes three

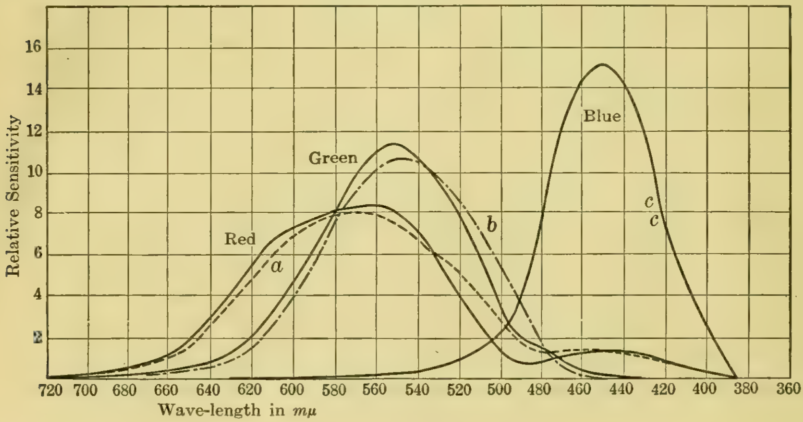


Fig. 84. Color Curves.

modes of response in the eye, not anatomically identified, but corresponding to three fundamental color sensations — red, green and blue. Figure 84 (solid lines) may be regarded as indicating the degree to which each wave-length of the spectrum has the power to excite these separate processes. The curves were deduced from a long series of experiments in the mixture of lights from the various parts of the spectrum in accordance with the following hypothesis: A portion of the spectrum included between any two ordinates, excites the three processes in proportion to the three included areas under the three curves respectively; a mixture of two such portions, as the three sums

of the areas; and two mixtures will match when the three sums — for the red, green and blue curves — are equal each to each. Thus the curves are a condensed statement of the facts of color mixture. Furthermore, over certain parts of the spectrum, one color may be mixed with some other color to form white. The curves are so drawn that in such a case the sums of the red segments, the green segments and the blue segments are all equal. Two such colors are said to be complementary. Thus the extreme red of the spectrum has a complementary in the bluish-green at wave-length 0.490–0.495 μ, while the extreme violet has a complementary in the greenish-yellow at wave-length 0.565–0.570 μ, the mid-region of the spectrum between these limits being unique in having no complementary in the spectrum. To complement it, two lights from the two end regions of the spectrum would have to be mixed.

So far, no mention has been made of a group of phenomena which are of great importance in connection with the theory of vision. This group includes the phenomena of contrast and the phenomena of after-images.

Contrast is noticed in a typical form when two different surfaces are seen in close juxtaposition. Thus, a small piece of gray paper looks lighter when placed on a black surface, darker on a white. When placed on a colored surface, in general it takes on a tinge of the complementary color; e.g., on red it looks greenish-blue, on yellow bluish, etc. This is known as simultaneous contrast. There is also an effect known as successive contrast; the appearance of an object is influenced in a similar way after looking at white, black, red, yellow, etc. An extreme case of successive contrast is the after-image. After one has gazed intently at a well-lighted pattern, the pattern will be seen when the eyes are shifted to a uniform field; it will be seen, in general, in brightness and in color negative and complementary to those of the original pattern.

According to Helmholtz, the phenomena of successive contrast and after-images arise from unequal fatigue of the color processes in the retina, so that subsequently the unfatigued components react more strongly under equal light. Hence the appearance of the complementary colors. Simultaneous contrast effects Helmholtz attributed to the "psychic" process of judgment, considering them quite analogous to the apparent reduction of stature of an ordinary man when seen alongside a giant. These explanations have lacked much of being satisfactory; a fact which led to a second type of theory of color vision, known as the theory of antagonistic colors.

Hering, the originator of this conception, took the ground that the

opposed or antagonistic (complementary) colors were attributable in some way to the breaking down, under the influence of light of certain wave-lengths, of a certain visual substance, and to the building up of the same substance under light of other wave-lengths. Thus, he supposed that red (e.g.) is due to the fact that a certain substance in the visual apparatus is chemically changed in some way by the red rays of the spectrum, and that when the red light is withdrawn, the change tends to reverse itself, resulting in a sensation of green. This would occur in some such manner as a muscle, when it is working, uses up a certain amount of its substances, which is automatically restored while the muscle is subsequently at rest. Thus, there is the green after-image, and successive contrast in the direction of green. Hering further postulated that the action of red light on a certain part of the visual apparatus, in breaking down the corresponding visual substance in one part of the visual apparatus, called forth at the same time an increased building up of the same material in other parts, in this way explaining simultaneous contrast in the direction of green. The following scheme indicates the way in which this theory interprets the various color sensations, including white and black. In physiological terms, the breaking down of tissue substance is referred to as **dissimilation** or **katabolism**, the building up as **assimilation** or **anabolism**.

Phase	*Sensory effect* 1	2	3
Breaking down, dissimilation, or katabolism	Red	Yellow	White
Building up, assimilation, or anabolism	Green	Blue	Black

These three hypothetical components of the visual process are referred to as the red-green substance, the yellow-blue substance and the white-black substance.

Even though not accepting this theory in its original form and tying up the opposed or complementary color processes with the physiological construction and destruction of tissue substance, as this view of color-vision does, one is compelled by the facts to group the various visual qualities — the colors, including white, black, etc. — in some such way. This implies that the colors of the opposed pair are antagonistic or incompatible in the sense that they cannot coexist. It is possible to see red and green at once, or yellow and blue at once, but not in the same place. A reddish-green or a yellowish-blue is unthinkable — the two cancel each other just as acid and alkali cancel each

other in the same solution, usually leaving an excess of one or the other, but not of both, the two having offset each other's characteristics in forming a neutral salt. In the case of the mixture of antagonistic colors, the mutual cancellation results in a gray, or in a color resembling one or the other of the components with an admixture of gray, greater or less according to circumstances.

By way of summary, it is to be said that these two theories have been described as being typical, and each as representing a certain group of facts. The three-component theory, originally proposed by Young, and developed by Helmholtz and his followers, takes account of the experimental facts of color-mixture and of certain facts noted in cases of color-blindness; while the theory of antagonistic pairs of colors is based primarily on other groups of facts, those relating to after-images and to contrast. It would thus be difficult to give preference to one of these views to the exclusion of the other. It is rather to be said that a complete account of color-vision is less simple than either, and will have to include as much of both theories as is essential to the facts.

Lighting and Vision. — An important question, which has not in the past been as well understood as it should be, is: "What determines the amount of the light-flux acting upon one element of the retina, say upon one rod or upon one cone?"

Obviously, this amount of flux is proportional to the illumination upon the retina. If one thinks of a small part of an image upon the retina, this part will be described by stating its area and its illumination. It is due to a certain light-flux which enters the pupil and which comes from that part of a surface, outside the eye, which is so imaged. For the eye, any such element of surface, forming part of the object seen, is essentially a source of light and may be treated as such. It has a certain brightness, b, which, multiplied by its radially projected area, Δs, gives the luminous intensity of the element in the direction from which the brightness has been measured.[1] If the eye is at a distance r, the illumination at the eye due to the element s will be:

$$E = b\Delta s \cdot \frac{1}{r^2}$$

[1] The photometric terms used here, notably the terms luminous flux, luminous intensity, illumination and brightness, and the corresponding concepts have been defined (pp. 165–170, 174). The significance of the discussion which follows rests upon a clear understanding of what is meant by these terms, and notably upon the difference between illumination and brightness, which, as different things, are on no account to be confused.

and the flux reaching the retina:

$$F = b\Delta s \cdot \frac{1}{r^2} \cdot p \cdot k$$

where p is the area of the pupil measured in air and k is the fraction of the flux which reaches the retina owing to absorption by the eye media. This flux is distributed over an area $\Delta s'$ on the retina, which is the image of Δs; hence the illumination at the retina is

$$E' = b \cdot \frac{\Delta s}{\Delta s'} \cdot \frac{1}{r^2} \cdot p \cdot k.$$

If l is the focal length of the eye, $\frac{\Delta s}{\Delta s'} = \frac{r^2}{l^2}$ and by substitution:

$$E' = \frac{pk}{l^2} b$$

in which k and l are constants for any eye, and p is the diameter of the pupil, constant for all parts of the retina at any instant of time. There follows the proposition:

The illumination at any point upon the retina is directly proportional to the brightness, measured in the direction of the eye, of the surface imaged at that point.

Let the reader take a piece of mirror, a piece of clean white blotting paper and a piece of the same blotting paper soaked in ink and dried, and place these three side by side on a table top under a good and uniform illumination. He will find that the brightness of a surface depends not only upon the illumination, but also upon the character of the surface illuminated, whether it reflects a large or small fraction of the incident light (comparing the white and the darkened blotting papers) and upon the character of the reflection, whether it is diffuse as in the case of the blotting paper, or direct (specular) as in the case of the mirror or, as in most practical cases, something partaking of both characters, as a glossy paper or polished woodwork. It is only in exceptional cases that the brightness of a surface can be readily calculated from the illumination. More often, the only way to know the brightness is by measuring it directly from the direction of the eye, which in most cases involves a fairly simple photometric measurement.

Imagine the eye (or less accurately the two eyes) at the center of a spherical surface, upon which any visible point in the surroundings can be radially projected and located as to meridian and departure from the line of fixation; and in addition specify for each point the brightness (and color) of the element of the field so projected. This

comprises a complete account of the surrounding conditions as they affect vision. While these data depend upon illumination, they are *not* illumination data but *brightness* data; and if they are unfortunately difficult, in any case, to derive from the illumination, and bear a wholly different relation to the illumination in different sorts of work and in the case of different sorts of visual objects, the engineer must bear in mind that they are nevertheless the data upon which the performance of the eyes will depend, and as such are of the very first importance in lighting.

When the conditions that affect the eyes have been defined in photometric terms, that is, in terms of *brightness*, and when a certain understanding of the intensity of the stimulus acting upon any portion of the retina has been arrived at, the analysis of the phenomena of vision must go further, and show *how* the facts of vision depend upon the intensities of stimulation so expressed. With a given brightness before the eye, and consequently with a given illumination or flux density upon the retina, what follows in vision? Or, in other words, what does one actually see?

It is found at once that there is no simple one-to-one relation between photometric brightness and its visual appearance, in spite of the simple relation between brightness and the intensity of retinal stimulation. This may be understood at once by considering the simple fact that an object, such as a printed page, when examined under the lowest illumination at which it is easily read has just about the same appearance as under the highest illumination that can be used with comfort. Direct sunlight furnishes an illumination stated as 6000 to 10,000 foot-candles, diffused daylight from bright clouds only a fraction of this, and 2 or 3 foot-candles makes reading fairly easy.

Knowing that the ink has perhaps $\frac{1}{15}$ to $\frac{1}{20}$ the reflection factor of the paper, simple arithmetic will show that the ink under some of these conditions has actually a higher brightness than the paper has under others. And yet under all these conditions the ink constantly looks black and the paper constantly white.

Operation of the same principle in the opposite sense takes place in numerous simple experiments. For example, two small pieces of gray paper, placed one upon a sheet of white, the other upon a sheet of black, will appear dark and light respectively when compared with each other. That is, the same brightness will look different under different conditions. This experiment may be varied in many ways, and incidentally applies to apparent color as well as to apparent brightness. The following is a general statement of the facts: an object of certain brightness and color tends to appear altered in a sense opposite to the

visual appearance of the background or adjacent areas — it will appear darker on a lighter background and *vice versa*, and will tend to take on a color complementary (antagonistic) to that of the juxtaposed area. This effect is mutual between any two areas: each one reacts upon the other. It is greater, the greater the area which induces the contrast, so that in the case cited the effect appears to be limited to the small, completely surrounded field; and it is greater, the closer the juxtaposition, so that in a closed field, the effect is sensibly at a maximum with a limited area of background.

This phenomenon of contrast, instead of being a laboratory curiosity, or a mere "optical illusion," is an expression of a quite fundamental fact of vision, which is always present. Its result is the approximate constancy of appearance of objects under widely varying changes in the lighting, and it becomes evident in a startling way under certain specially devised conditions, such as those of the experiments described, which are not commonly encountered in the ordinary use of the eyes. This fundamental may be somewhat more briefly stated by saying that the visual organs have a tendency to refer brightness and color to a standard which is some sort of a mean of the field, and that vision is therefore a relative measure of brightness and color, with a comparatively feeble power of absolute judgment. The importance of this for the survival of the individual, speaking from the evolutionary standpoint, will be recognized when one reflects that he is primarily interested in interpreting, not light-intensities at all, but *objects* under widely varying intensities and colors of illumination.

Furthermore, this relativity of vision, which one may speak of as compensatory or adaptive in character, is only approximate and by no means mathematically exact. It obviously breaks down at extremes; in twilight illumination, and on the other hand at dazzlingly high illumination, objects no longer appear as they do under that wide intermediate range of illuminations which afford fairly clear and comfortable vision; and even within this range, careful experimentation shows that vision behaves differently at different levels of light intensity.

The Limits of Vision. — In complete harmony with what has just been said is the fact that the least difference in brightness which can be perceived (**differential threshold**) is not a constant but is more nearly a constant fraction of the brightness itself. This fact is spoken of as Weber's Law and it is true, within limits, not only for vision but for other senses as well. For vision the fraction is stated as 1 per cent, so that, in general, two brightnesses which are in the ratio of 1 to 1.01 will appear as just different. The values obtained for this fraction are somewhat diverse and depend upon the manner in which the bright-

FIG. 85. Brightness-Difference Threshold as a Function of the Ratio of Field Brightness to that of Surroundings.

nesses are presented to the eye, upon their extent in the visual field, and upon various other details of the experimental technique. A very complete set of such results obtained years ago gave the critical difference as about 1.7 per cent, nearly constant for various brightness levels over a fairly wide range, and increasing above and below this range. On the other hand, under different conditions of experiment, the fraction may fall as low as 0.5 to 0.7 per cent (Fig. 85). In this connection it is to be remarked that the contrast sensitivity of the eye is seriously reduced if the areas compared are seen on a background much brighter than themselves; or, more generally, if a relatively large light-flux enters the eye from other directions, as from a light source within the field of vision; and also to a minor extent if the fields compared are seen on a much darker background. That is to say, the question is thus complicated by the contrast conditions of the experiment, in addition to the extreme absolute brightness or dimness of the observed fields and the other incidental conditions enumerated above.

It will appear that the contrast sensitivity of the eye is the important factor in photometry. The disadvantage of viewing the photometric field on a dark background, as it is ordinarily seen when looking into the tube, is probably offset by certain advantages gained by that arrangement. On the other hand, the photometrist should, if possible, see that the working field of his instrument is neither at too high nor too low a brightness to give the most sensitive settings. The final test of the sensitivity is, of course, the reproducibility of his settings under identical conditions as indicated by the probable error computed from a series of readings.

There is an absolute limit to the sensitivity of the eye for brightness. The least brightness visible in the dark (**absolute threshold**) is in a high degree dependent upon the recent exposure of the eyes to light. On coming into a dark room from bright light the threshold is found to be a progressively diminishing quantity, reaching a final minimum in the course of one hour or so. Its initial value has been found to be as much as 1500 to 8000 times this ultimate minimum. This is quite in line with the well-known temporary inability to see in dim light, which one might say is due to the relative blinding effect of the brightness from which the eyes have just come. However, to speak of it as "blinding" may be misleading, since it is a condition better adapted to vision at those higher brightnesses than is the dark-adapted state which follows a stay in darkness. The return to the light-adapted state is much more rapidly effected than the change from light- to dark-adaptation.

The engineer should consider these facts in lighting practice, and

avoid conditions which involve sudden alterations in illumination, as in going from a brightly lighted room into a dimly lighted passageway, or turning from a brightly lighted machine to find a tool in a dimly lighted place. Such conditions are productive of delays in the progress of work and may lead to accidents, easily avoidable by well-considered lighting.

The smallest visible object is measured by its visual angle, that is, by the angle it subtends at the eye. The well-known ophthalmologists' test card is a series of lines of different-sized letters, each of which is designated by the distance at which it subtends a standard visual angle. Thus, the letters of the 20-foot line subtend 5 minutes in height at 20 feet, and the width of each stroke of the letter subtends 1 minute. The letters of the 40-foot line subtend the same angles at 40 feet or twice these angles at 20 feet, and so on for the other lines. Usually the series begins at the top with a single 200-foot letter, and runs something as follows: 120, 80, 60, 40, 30, 20, 15, 10 feet. Visual acuity is recorded as a fraction, the numerator of which is the actual distance of the subject from the test card, and the denominator the nominal distance of the smallest line that is legible at that actual distance. Thus, $V = 20/30$ means that the subject just reads the 30-foot line at 20 feet. Although 20/20 is considered normal in practice, many persons test 20/15 and some as high as 20/10. The one-minute standard (20/20) is therefore rather to be looked upon as passable than as the normal.

It has been estimated that one retinal cone in the center of the retina, where clear seeing takes place, corresponds in size almost exactly to the optical image of an object subtending one minute angle in the visual field, and the "limit of resolution" of the eye has been thought to depend upon this fact. While this may be true with sufficient light, it must be remembered that in dim light the least visual angle is much greater than this, and that visual acuity is a value which for a given eye increases with the light intensity. Furthermore, it must not be forgotten in this connection that in any image-forming optical system a point in the object is represented in the image, not by a point, but by a very small diffusion circle. The effect of this fact is that while the relation which was shown to exist between the brightness of the object and the flux-density at the retina $\left(E' = \frac{pk}{l^2} b\right)$ holds very well for larger areas it breaks down when, as in the case of normal visual acuity, the size of the image comes to be of the same order as the size of the diffusion circle. In such a case the image cannot be treated as a reduced counterpart of the object, but becomes very much blurred in

outline and therefore correspondingly reduced as to contrast. Visual acuity involves two factors, the geometric image-forming power of the eye as an optical instrument, and certain physiologic properties of the retina which are less well understood.

The pupil of the eye reacts by a contraction in size with increase in light-intensity and a dilatation with decrease. The effect of the size of the pupillary opening is two-fold. First, it results in a relative change in the illumination of the retinal image, nearly proportional at all points. This favors the retina by the resulting momentary partial compensation of sudden changes in the external light conditions, until the eye can adapt itself to them. Obviously it can have little effect on vision by contrast, since this is principally a relative matter, as has been seen. It would, however, have a tendency to modify the least brightness perceptible, which would obviously have to be increased in proportion if the pupillary area were to be artificially reduced without otherwise disturbing the eye.

A second effect of the pupillary size is to modify the sharpness of the image. This works in two ways. Owing to the wave-nature of light, the diameter of the diffraction pattern which is the image of a point is smaller the larger the aperture. And on the other hand, a larger pupil permits more of the irregularities in the refracting surfaces of the eye to participate in the refraction, and the image of the point is thereby increased in size. As a matter of fact, where the refractive errors of the eye are larger than normal, a contracted pupil increases visual acuity; whereas with eyes possessing what may be called good vision an optimum visual acuity is obtained when the pupil is of 3 to 4 mm. diameter, where the compromise between these two factors is evidently the best. This result appeared from a series of experiments on visual acuity with artificial pupils, and it is interesting to note the agreement of the result with the "physiological" diameter of the pupil above mentioned.

Up to this point the limit of vision has been discussed from two standpoints: first, the "intensity" threshold, the least brightness or brightness difference which will determine a response; and second, the least size (visual angle). There is a third factor involved: the time that a stimulus must act to be effective (**time threshold**).

It should be evident without further explanation that every object which is visible, or better, every image which makes an effective impression upon the retina, (1) must be differentiated from its background by a certain amount, (2) must cover a certain area of the retina, and (3) must endure for a certain period of time. In the case of contrast the fact was mentioned that the threshold for brightness differ-

ence depends upon the areas compared. In the measurement of the least visual angle, as with the letter-chart described, the contrast is high, being of the grade induced by black ink on white paper under equal illumination. If the ink be reduced to a pale gray, thereby reducing the contrast, the smallest legible letters will be larger than in the case of the black ink.

In neither of these cases has the time of action of the test object been considered. It has been supposed to be made adequate for easy observation on the part of the subject. Indeed, it is fair to suppose that beyond a very few seconds, there is no increase in the probability of a given object being seen by further increase in the time of exposure, provided the eye is initially in a state of adjustment for the conditions and does not undergo further adaptive or other adjustment. If however, the action-time of the test object be reduced to a fraction of a second, such as 1/8 or 1/40, the case is different. The same object, just visible with leisurely observation, will become invisible and will have to be increased either in size or in point of contrast to become again distinguishable. It has been established, approximately at least, that within certain limits there is a reciprocal relation among the three, brightness (or contrast), size and time, such that if one be decreased one of the others must be increased in proportion in order that the object shall, in both cases, be just at the point of visibility. The limits that have been stated are: in size, up to 2° in the visual field; in time, up to about $\frac{1}{8}$ second.

The importance of the time factor will be evident from certain facts that have appeared from the study of the eye-movements. It is only exceptionally that the eyes rest upon any object for a length of time. In rapid work such as in reading, the eyes do not glide along the line of print as it is read, but jump along, making a few stops, perhaps two to seven in an ordinary line, the movements each occupying a few hundreths of a second and the pauses from 0.07 to 0.25 second. It is during these pauses only that an effective impression upon the retina can be made, and thus it would appear that for rapid work of any kind there is a fairly definite lower limit of stimulation-time determined by the possibilities of the muscles and of the nervous system upon which they depend. It is probable that the eyes, as well as the hands, may be so trained in a series of predetermined movements, such as a routine factory or office operation, that they will execute their proper movements in less time than has been shown experimentally. It is not known, however, how far this mechanical limit of the "natural" exposure time of the eyes may be reduced by practice.

Injuries from Radiation. — Two undoubted forms of injury due to radiation may be encountered in practice. They are characteristically different, although in some cases resulting from identical exposure.

1. Blinding from too strong light, as in looking at the sun or other light source of high brightness. This may also result from exposure to an electrical short-circuit flash of high energy, as in a power house, and has afflicted mountain climbers in the snow-fields at high altitudes. The blinding may be transient or may last for several hours, or may result in ocular disturbance persisting for weeks.

This disturbance would seem to have its seat in the retina and to be due to the visible radiation exclusively. The ultra-violet and the infra-red rays have been shown not to penetrate as far as the retina, except in extremely limited spectral regions adjacent to the visible.

2. **Ophthalmia electrica** is a painful inflammatory disturbance of the conjunctiva, the mucous membrane which covers the front of the eyeball and lines the lids. Its onset is usually delayed until some hours after exposure. It begins with pricking and burning sensations in the eyes and extreme sensitiveness to light. Pain follows, accompanied by swelling and the discharge of pus. In the course of ten days or so the eyes return to normal. Mild cases do not reach the extreme state described, going no further than the painful condition, and recovering over night. A similar condition may affect the exposed skin. This has been called **dermatitis electrica** and is quite similar in character to sunburn of a corresponding degree.

These disturbances follow exposure to radiation rich in ultra-violet light, such as electric power-flashes, arc lamps, quartz-mercury lamps, etc. They are effectually prevented by a layer of glass (such as an ordinary spectacle lens) between the body surface and the source, as the glass absorbs the extreme ultra-violet rays. Furthermore, these affections are very superficial in character, since the ultra-violet rays are not able to penetrate far into the tissues.

Contrary to opinions which have been expressed, ordinary light sources, as they are actually used, do not constitute a danger to the eyes from their ultra-violet content. As a matter of fact, daylight, under not unusual conditions, contains far more ultra-violet radiation than the light from any artificial source as used in lighting.

There is no evidence that the infra-red rays have resulted in injury. At least, no characteristic disease has been discovered in the many years that large numbers of men have been employed in iron and steel mills and in other occupations where they are exposed to the infra-red radiation in large amounts. This is probably for the reason that the

immediate heating effect of the infra-red is painful and is an unmistakable warning which leads the individual to protect himself at once.

COLLATERAL READING

Physiological Optics

Howell, Text-Book of Physiology (Philadelphia, 1921, 8th edition).

Bouasse, H., Vision des Formes et des Couleurs (Librairie Delagrave, Paris, 1917).

Troland, L. T., The Present Status of Visual Science, Bull. Nat. Research Council, V., Part 2, No. 27 (Washington, 1922).

Cobb, P. W., Photometric Considerations Pertaining to Visual Stimuli, Psych. Rev., **23**, 71–88 (1916).

Cobb, P. W., The Effect on Foveal Vision of Bright Surroundings, J. Exper. Psych., **1**, 419–425, 540–566 (1916).

Cobb, P. W., The Relation between Field Brightness and the Speed of Retinal Impression, J. Exper. Psych., **6**, 138–160 (1923).

Cobb, P. W., Some Experiments on the Speed of Vision, Trans. I. E. S., **19**, 150 (1924).

Verhoeff, F. H., The Pathological Effects of Radiant Energy on the Eye, Proc. Am. Acad. Arts Sci., **51**, 629 (1916).

Luckiesh, M.; Taylor, A. H., and Sinden, R. H., Data Pertaining to Visual Discrimination and Desired Illumination Intensities, J. Frank. Inst., **192**, 757 (1921).

Nutting, P. G., The Fundamental Principles of Good Lighting, J. Frank. Inst., **183**, 287 (1917).

CHAPTER V

FUNDAMENTAL PRINCIPLES OF ILLUMINATION

[Ward Harrison]

The Light Distribution Curve

Pictorial Representation. — Figure 86 represents a common method of showing the manner in which the candlepower of a unit measured at different angles can be recorded. The value at any angle represents the average candlepower of the source at that angle as the source rotates about its vertical axis. A distribution curve is a graphical —

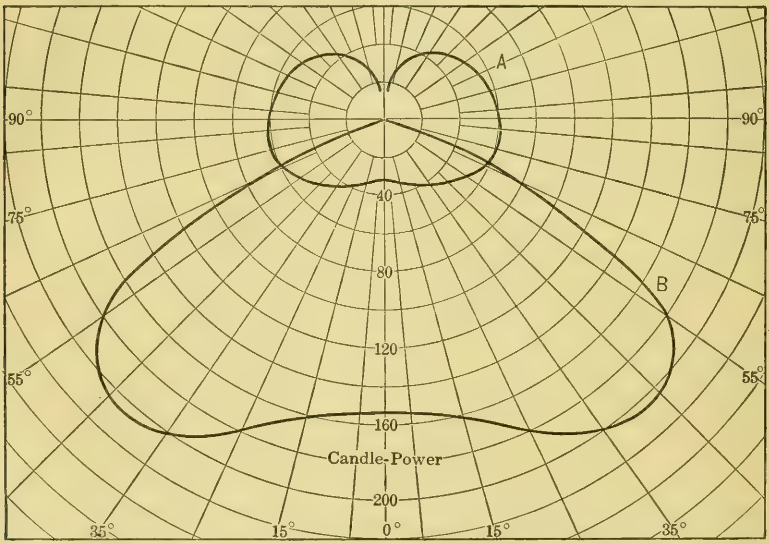


Fig. 86. The Area of a Distribution Curve is not a Criterion for Judging Light Output. These Two Curves Represent Equal Light-Outputs.

A — Distribution Curve of a Lamp in an Opal Globe.

B — Same Lamp in a Reflector Similar to that Shown in Fig. 109.

not a pictorial — representation of the light distribution from a source, although its general shape might convey the contrary impression. It is simply a convenient engineering method of presenting tabulated data graphically.

The area of a distribution curve is not a criterion of the total amount of light emitted by a source. In Fig. 86 both curves shown are taken from units giving exactly the same total lumens with different distributions of candlepower; although Curve *B* appears to represent much more light than Curve *A*, the amount of light given off is the same in each case.

Interpretation of Mean Spherical Candlepower. — Another common error in regard to distribution curves is to assume that simply taking the arithmetical average of the candlepowers at different angles as shown on the distribution curve will give the mean spherical candlepower of the unit represented. To make the true relation clear, assume that a May-pole is set up at the middle of a hemispherical hollow and that one girl carries a streamer making an angle of 45 degrees with the vertical and another carries one making an angle of 15 degrees with the vertical. Owing to the contour of the ground about the pole, both ribbons will be of the same length. Now, keeping the candlepower distribution curves in mind, assume that the top of the pole is the light source under consideration and that the length of each streamer represents the candlepower in its particular direction. It is obvious that in order to make one revolution about the pole, the girl holding the 45-degree streamer must travel a much greater distance than the other. In other words, she makes a bigger contribution to the general effect produced by the May-pole. In fact, because of the greater circle she must describe, she has to do 2.7 times as much work as the girl carrying the 15-degree streamer. In the erroneous use of a distribution curve just referred to, only the length of the ribbon is taken into consideration. From the analogy it is apparent that the zone of travel of the ribbon, or the complete zone in which the candlepower at a given angle is effective, must also be taken into account. Just as with the May-pole illustration the girl taking the 45-degree circle does 2.7 times as much work as the girl in the 15-degree circle, so the quantity of light (luminous flux) necessary to maintain an intensity of one candle throughout the 45-degree zone forms 2.7 times as big a part of the total light output of the lamp as the quantity of light required to maintain one candle at 15 degrees. In other words, the farther up from the vertical and toward the horizontal the candlepower shown on the distribution curve, the more weight it must be given as regards its contribution to the total quantity of light emitted by the source.

Flux Computation. — In computing the total flux of light in various zones, it is usually found convenient to calculate for zones of 10 degrees. Considering a uniform source of 1 candlepower contained in a sphere having a 1-foot radius, and dividing the surface of this sphere

into 10-degree zones, Fig. 87, it is evident that since the intensity of light on all parts of the surface of this sphere is 1 foot-candle, the number of lumens falling within any zone is numerically equal to one times the area of the surface of that zone in square feet.

$$\text{Lumens} = \text{foot-candles} \times \text{square feet.}$$

Again, if one places in the sphere a source whose candlepower distribution curve shows an average of 18 candlepower in the 80–90 degree zone, then the total lumens emitted by the source in that zone equals

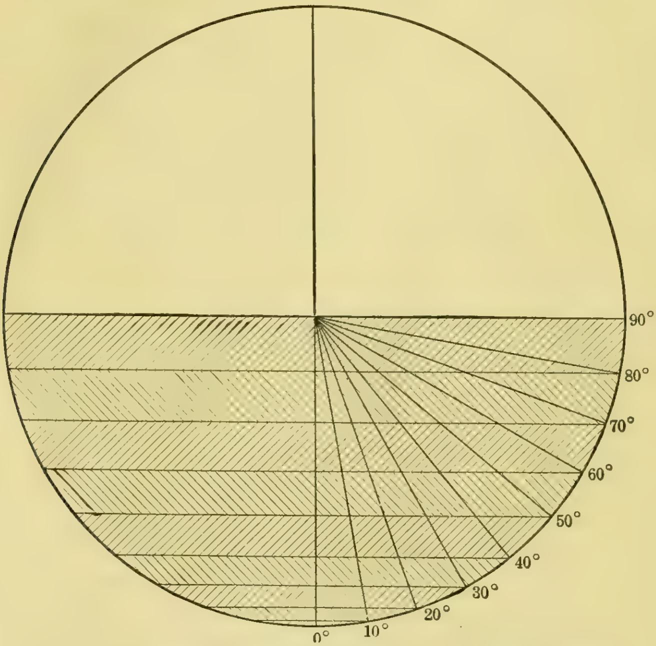


Fig. 87. Surface of Sphere Divided into 10-Degree Zones.

18 times the area of the zone in square feet. In other words, to find the lumens emitted in any zone when the candlepower is known, multiply the average candlepower directed into that zone by the area in square feet of that zone on a sphere of 1 foot radius. Table XXX, page 253, gives the areas of these zones (the multiplying factors) for each 10 degrees.

To use these factors with the curve of any light unit, take the candlepower at 5 degrees and multiply it by the 0–10 degree factor to obtain lumens in the 0–10 degree zone; take the candlepower at 15 degrees and multiply it by the 10–20 degree zone factor to obtain the lumens in the

10–20 degree zone, etc. The total lumens for any large zone, for example in the lower hemisphere, is the sum of the lumens thus determined in all of the 10-degree sections.

TABLE XXX

AREAS OF ZONES

Zone		Area on Unit Sphere
0°–10°	170°–180°	0.0954
10°–20°	160°–170°	0.283
20°–30°	150°–160°	0.463
30°–40°	140°–150°	0.628
40°–50°	130°–140°	0.774
50°–60°	120°–130°	0.897
60°–70°	110°–120°	0.992
70°–80°	100°–110°	1.058
80°–90°	90°–100°	1.091

Illumination Computation. — In consequence of the Inverse Square Law, if light rays are perpendicular to the plane of illumination, $E = \frac{I}{d^2}$ where E is the illumination, I the candlepower of the source in the direction of the plane, and d the distance from the source to the plane. Where the rays are not perpendicular the formula becomes $E = \frac{I \cos \propto}{d^2}$ where $\propto$ is the angle between the rays and the normal to the plane and d is the distance from the source to the point on the plane intercepted by the rays in question. If the plane be horizontal and h is the distance of the source above the plane, then

$$d = \frac{h}{\cos \propto} \text{ (Fig. 88)}$$

and

$$E = \frac{I \times \cos^{\cancel{2}\,3} \propto}{h^2}.$$

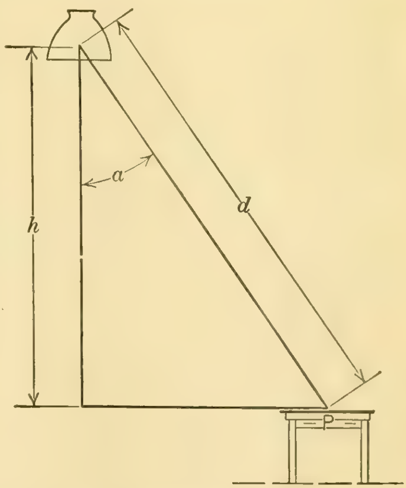


FIG. 88. Illumination on Surface Not at Right Angles to Light Rays.

Table XXXI, page 255, gives values for $\propto$ and $\frac{\cos^3 \propto}{h^2}$ for various heights

(feet) of a lamp above the plane and for horizontal distances (feet) from a lamp, when $I = 1$.

Candlepower Distribution Curves. — The calculation of illumination intensities in accordance with the formula just given, commonly known as the point-by-point method, required that the candlepower of the source at various angles ($\propto$) should be known, and to this end the use of the polar-distribution curve was generally adopted. The greater simplicity (and accuracy) of the lumen method of computation has resulted in the point-by-point method falling into disuse so far as interior lighting is concerned, and distribution curves are now employed principally for comparing the suitability of reflectors for use in a given location from the standpoint, particularly, of light distribution and light absorption.

Reflecting and Diffusing Media. — The light from a bare lamp is distributed in such a manner that under most conditions it cannot be employed effectively without the use of reflectors or enclosing glassware. Such accessories should not only direct light which would otherwise be ineffective into useful angles, but should serve the additional purposes of modifying the brilliancy of the source and diffusing the light to produce a soft and pleasing illumination.

Three systems of lighting are commonly employed. They are usually termed direct, indirect and semi-indirect. In the so-called direct-lighting system, the unit distributes the light downward into the room; in the indirect system, all of the light is thrown upon the ceiling and thence reflected into the room; in the semi-indirect system, a greater part of the light is thrown upon the ceiling but some of it passes through the bowl and directly into the room.

In each of these systems, various reflecting surfaces and transmitting media are used, and a knowledge of the action of such surfaces and media in the utilization of light is necessary to a proper selection of equipment.

TABLE XXXI

Angle Between Light Ray and Vertical, and Intensity of Illumination in Foot-candles on a Horizontal Plane Produced by a Source of One Candle-power

Height of Unit above Plane, Feet	Horizontal Distance from Unit, Feet: 0	1	2	3	4	5	6	7	8
4	0° 0′ .062500	14° 2′ .057070	26° 34′ .044720	36° 52′ .032000	45° 0′ 022100	51° 20′ .015240	56° 19′ 010660	60° 15′ .007640	63° 26′ 005590
5	0° 0′ .040000	11° 9′ .037710	21° 48′ .032020	30° 58′ .025220	38° 40′ .019040	45° 0′ 014140	50° 11′ .010500	54° 28′ .007850	58° 0′ 005950
6	0° 0′ .027780	9° 28′ .026730	18° 26′ .023720	26° 34′ .019870	33° 42′ .016000	39° 48′ .012600	45° 0′ .009820	49° 24′ .007660	53° 8′ 006000
7	0° 0′ .020410	8° 8′ .019800	15° 57′ .018140	23° 12′ .015850	29° 45′ .013360	35° 32′ 011000	40° 37′ 008930	45° 0′ .007220	48° 49′ .005830
8	0° 0′ .015630	7° 8′ .015270	14° 2′ .014270	20° 33′ .012830	26° 34′ .011180	32° 0′ .009530	36° 52′ 008000	41° 10′ .006400	45° 0′ .005520
9	0° 0′ .012350	6° 20′ .012120	12° 32′ .011480	18° 26′ 010540	23° 55′ 009430	29° 3′ 008250	33° 42′ 007110	37° 52′ 006070	41° 38′ 005150
10	0° 0′ .010000	5° 43′ .009850	11° 19′ .009430	16° 42′ .008790	21° 48′ .008010	26° 34′ .007160	30° 58′ 006310	35° 0′ .005500	38° 40′ .004760
11	0° 0′ .008260	5° 12′ .008160	10° 18′ .007870	15° 15′ .007420	19° 59′ .006860	24° 27′ .006230	28° 37′ 005590	32° 28′ .004960	36° 2′ 004370
12	0° 0′ .006940	4° 46′ .006870	9° 28′ .006680	14° 2′ .006340	18° 26′ .005930	22° 37′ .005460	26° 34′ .004970	30° 15′ .004480	33° 42′ .004000
13	0° 0′ .005920	4° 24′ .005870	8° 45′ .005710	13° 0′ .005470	17° 6′ .005170	21° 2′ .004810	24° 46′ .004470	28° 18′ .004040	31° 34′ 003660
14	0° 0′ .005100	4° 5′ .005060	8° 8′ .004950	12° 6′ .004770	15° 57′ .004540	19° 39′ .004260	23° 12′ 003960	26° 34′ .003650	29° 45′ .003340
15	0° 0′ .004440	3° 49′ .004420	7° 36′ .004330	11° 19′ .004190	14° 56′ .004010	18° 26′ .003800	21° 48′ .003560	25° 1′ .003310	28° 4′ .003050
16	0° 0′ .003910	3° 35′ .003880	7° 8′ .003820	10° 37′ .003710	14° 2′ .003570	17° 25′ .003390	20° 33′ .003210	23° 38′ .003000	26° 34 002800
17	0° 0′ .003460	3° 22′ .003440	6° 42 .003390	10° 0′ .003310	13° 15′ .003190	16° 24′ .003060	19° 26′ 002900	22° 23′ .002740	25° 12′ 002560
18	0° 0′ .003090	3° 11′ .003070	6° 20′ .003030	9° 28′ .002970	12° 32′ .002870	15° 32° .002760	18° 26′ .002640	21° 14′ .002500	23° 55′ .002360
19	0° 0′ .002770	3° 1′ .002760	6° 0′ .002730	8° 58′ .002670	11° 53′ .002600	14° 45′ .002510	17° 31′ .002400	20° 13′ 002290	22° 50′ .002170
20	0° 0′ .002500	2° 51′ .002490	5° 43′ 002460	8° 32′ .002420	11° 19′ .002360	14° 2′ .002280	16° 42′ .002190	19° 17′ .002100	21° 48′ .002000
21	0° 0′ .002265	2° 44′ .002258	5° 26′ .002236	8° 8′ .002200	10° 47′ .002150	13° 24′ .002095	15° 57′ .002014	18° 26′ .001935	20° 51′ .001850
22	0° 0′ .002065	2° 36′ .002060	5° 10′ .002047	7° 46′ .002010	10° 20′ .001963	12° 48′ .001915	15° 15′ .001852	17° 39′ .001786	20° 0′ .001711
23	0° 0′ .001890	2° 29′ .001890	4° 58′ .001868	7° 26′ .001841	9° 52′ .001807	12° 16′ .001763	14° 37′ .001711	17° 9′ .001649	19° 11′ .001592
24	0° 0′ .001736	2° 23′ .001730	4° 45′ .001715	7° 7′ .001695	9° 30′ .001662	11° 46′ .001628	14° 2′ .001582	16° 16′ .001535	18° 25′ .001480
25	0° 0′ .001600	2° 17′ .001595	4° 34′ 001584	6° 51′ 001565	9° 5′ .001540	11° 19′ .001508	13° 30′ .001470	15° 39′ .001427	17° 45′ .001381

TABLE XXXI

Angle Between Light Ray and Vertical, and Intensity of Illumination in Foot-candles on a Horizontal Plane Produced by a Source of One Candle-power. — *Continued*

Height of Unit above Plane, Feet	Horizontal Distance from Unit, Feet: 9	10	11	12	13	14	15	16	17	18
4	66° 2′ .004190	68° 12′ .003200	70° 1′ .002490	71° 34′ .001980	72° 54′ .001590	74° 3′ .001300	75° 4′ .001070	75° 56′ .000900	76° 46′ .000750	77° 30′ .000640
5	60° 57′ .004580	63° 26′ .003580	65° 34′ .002830	67° 25′ .002280	68° 58′ .001850	70° 21′ .001520	71° 34′ .001260	72° 39′ .001060	73° 37′ .000900	74° 25′ .000770
6	56° 19′ .004740	59° 3′ .003780	61° 23′ .003050	63° 26′ .002490	66° 13′ .002050	66° 48′ .001700	68° 12′ .001420	69° 27′ .001200	70° 34′ .001020	71° 25′ .000880
7	52° 7′ .004730	55° 1′ .003850	57° 31′ .003160	59° 45′ .002610	61° 41′ .002180	63° 26′ .001830	64° 59′ .001540	66° 23′ .001310	67° 37′ .001130	68°45′ .000970
8	48° 22′ .004580	51° 20′ .003810	53° 59′ .003180	56° 19′ .002670	58° 24′ .002250	60° 15′ .001910	61° 55′ .001630	63° 26′ .001400	64° 48′ .001210	66° 2′ .001050
9	45° 0′ .004370	48° 0′ .003700	50° 42′ .003140	53° 8′ .002670	55° 18′ .002280	57° 15′ .001960	59° 3′ .001680	60° 38′ .001460	62° 6′ .001260	63° 26′ .001100
10	41° 59′ .004110	45° 0′ .003540	47° 43′ .003050	50° 11′ .002630	52° 26′ .002270	54° 28′ .001960	56° 19′ .001710	58° 0′ .001490	59° 32′ .001300	60° 57′ .001150
11	39° 17′ .003830	42° 16′ .003350	45° 0′ .002920	47° 30′ .002550	49° 46′ .002230	51° 50′ .001950	53° 45′ .001710	55° 30′ .001500	57° 6′ .001320	58° 34′ .001170
12	36° 52′ .003560	39° 48′ .003150	42° 31′ .002780	45° 0′ .002460	47° 17′ .002170	49° 24′ .001910	51° 20′ .001690	53° 8′ .001500	54° 49′ .001330	56° 19′ .001190
13	34° 42′ .003290	37° 34′ .002950	40° 14′ .002630	42° 44′ .002350	45° 0′ .002000	47° 6′ .001870	49° 5′ .001660	50° 54′ .001480	52° 36′ .001330	54° 10′ .001190
14	32° 44′ .003040	35° 32′ .002750	38° 9′ .002480	40° 37′ .002230	42° 53′ .002010	45° 0′ .001800	46° 58′ .001620	48° 49′ .001460	50° 31′ .001310	52° 7′ .001180
15	30° 58′ .002800	33° 42′ .002560	36° 15′ .002330	38° 40′ .002120	40° 55′ .001920	43° 3′ .001740	45° 0′ .001570	46° 51′ .001420	48° 34′ .001290	50° 11′ .001170
16	29° 23′ .002590	32° 0′ .002380	34° 30′ .002190	36° 52′ .002000	39° 6′ .001830	41° 10′ .001670	43° 9′ .001520	45° 0′ .001380	46° 45′ .001260	48° 22′ .001150
17	27° 54′ .002390	30° 28′ .002220	32° 54′ .002050	35° 13′ .001890	37° 24′ .001740	39° 29′ .001590	41° 25′ .001460	43° 16′ .001340	45° 0′ .001220	46° 38′ .001120
18	26° 34′ .002210	29° 3′ .002060	31° 26′ .001920	33° 42′ .001780	35° 49′ .001650	37° 52′ .001520	39° 48′ .001400	41° 38′ .001290	43° 22′ .001190	45° 0′ .001090
19	25° 21′ .002050	27° 45′ .001920	30° 4′ .001800	32° 17′ .001670	34° 23′ .001560	36° 23′ .001450	38° 17′ .001340	40° 6′ .001240	41° 49′ .001150	43° 27′ .001060
20	24° 14′ .001900	26° 34′ .001790	28° 49′ .001630	30° 58′ .001580	33° 2′ .001470	35° 0′ .001370	36° 52′ .001280	38° 40′ .001190	40° 22′ .001110	41° 59′ .001030
21	23° 12′ .001760	25° 28′ .001668	27° 39′ .001575	29° 43′ .001435	31° 46′ .001394	33° 42′ .001306	35° 32′ .001222	37° 19′ .001140	39° 0′ .001065	40° 37′ .000992
22	22° 15′ .001637	24° 30′ .001553	26° 34′ .001477	28° 35′ .001398	30° 35′ .001318	32° 36′ .001240	34° 17′ .001139	36° 5′ .001088	37° 42′ .001023	39° 20′ .000955
23	21° 22′ .001525	23° 30′ .001456	25° 35′ .001386	27° 34′ .001316	29° 29′ .001246	31° 21′ .001177	33° 6′ .001111	34° 50′ .001045	36° 28′ .000984	38° 3′ .000923
24	20° 33′ .001425	22° 35′ .001365	24° 38′ .001302	26° 35′ .001240	28° 27′ .001180	30° 15′ .001118	32° 0′ .001059	33° 40′ .001000	35° 19′ .000943	36° 50′ .000890
25	19° 48′ .001332	21° 48′ .001280	23° 45′ .001226	25° 39′ .001171	27° 29′ .001117	29° 15′ .001063	30° 58′ .001009	32° 38′ .000955	34° 13′ .000905	35° 45′ .000855

Polished Metal and Mirrored Glass

Reflection. — The simplest form of reflection is that which takes place when a ray of light strikes a polished metal surface. As indicated in sketch A, Fig. 89, a ray of light having a direction Sa, on striking a polished metal surface, is reflected in the direction ab. The angle y (called the angle of reflection) is equal to the angle x (called the angle of incidence) and practically no light is reflected in other directions. This is called regular reflection. It will be seen, therefore, that it is possible to redirect light in any desired direction by means of such a surface properly placed. While all polished metal surfaces reflect light in the manner described, they do not reflect it in like amounts. For

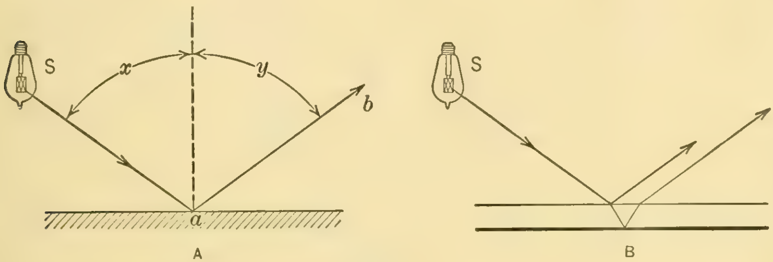


FIG. 89.
A — Reflection from Polished Surface.
B — Reflection from Mirrored Surface.

instance, if two beams of 100 lumens each fall respectively on a polished silver surface and on a polished aluminum surface, the silver will reflect approximately 88 lumens and the aluminum about 62 lumens. In other words, the silver surface will absorb only 12 per cent of the light while the aluminum surface will absorb 38 per cent. All of the light falling on an opaque surface is either reflected or absorbed by that surface.

Polished Surface Reflection. — The reflection characteristics of mirrored glass are similar to those of polished metal. Figure 89 B shows the path of a ray of light striking the surface of a commercial type of mirror with silvering on the back of the glass. A small part of the light is at once reflected by the polished surface of the glass without passing through to the silvered backing; the remainder passes through the glass to the silver, from which it is reflected through the glass again and out along a line parallel to the ray reflected from the upper surface. The fact that most of the light has to pass through the glass, both to and from the reflecting surface, makes the silvered mirror a less efficient reflecting surface than the polished silver itself. For in-

stance, if 100 lumens strike a mirror the reflections and absorptions are of the following order of magnitude: 8 lumens are reflected by the exposed surface of the glass; 12 lumens are lost by being absorbed by the silvered surface; and 5 lumens are absorbed by the glass, leaving 75 lumens which are reflected by the silvered surface, or a total of 83 lumens reflected; the loss in the glass depends on the quality of the glass. The deterioration of a polished metal reflecting surface in service is, however, a factor which usually more than offsets its higher initial efficiency.

Polished Surface Reflector. — To obtain a desired distribution from a polished metal or a mirrored surface, it is necessary that the contour of the reflector at each point be such that it makes equal angles with the incident ray at that point and the desired direction of light. For example, where approximately parallel rays of light are desired, as in the case of automobile headlights, the cross-section of the reflector will have to be that of a parabola. A hemispherical reflector, on the other hand, placed above the lamp with its center coinciding with the light source, will not concentrate the light at all but will nearly double the candlepower at each angle in the lower hemisphere, since each ray that strikes the reflector is reflected back along the same line, through the source, and into the lower hemisphere. Mirrored reflectors have a disadvantage in that they throw brilliant images of the filament, or striations, on the surfaces illuminated. In practice, these striations are often eliminated by corrugating the reflector or frosting the lamp with, however, some loss in the control of the light.

Since polished metal and mirrored surfaces follow the law of regular reflection, these surfaces are used in reflectors where the aim is to obtain accurate control of the direction of the light. Searchlights, automobile headlights, and floodlighting units are the most familiar applications of polished metal reflectors used for accurate light control. Mirrored glass, on account of its low absorption, is also widely used for both direct and indirect lighting units.

Dull-finished or Semi-matte Surfaces. — A dull-finished or semi-matte surface can be considered as one which has many small polished surfaces making innumerable slight angles with the general contour. A surface coated with aluminum paint affords a good example. When a shaft of light strikes such a surface, the individual rays are reflected at slightly different angles, but all in the same general direction, as shown in Fig. 90 *A*. This is known as spread reflection. The spread of the reflected beam, indicated by the angle between lines *ac* and *ad*, is dependent upon the degree of smoothness of the surface; the smoother the surface, the narrower the angle. When the reflecting surface is

viewed along the line ba, no distinct image of the light source is visible, but only a bright spot of light.

The reflection characteristics of dull-finished or semi-matte surface reflectors are similar to those of reflectors having polished surfaces with the exception that the light is redirected with less accuracy. The efficiency of dull-finished reflectors in the deep-bowl shape, for example, unless they are carefully designed, is likely to be reduced considerably

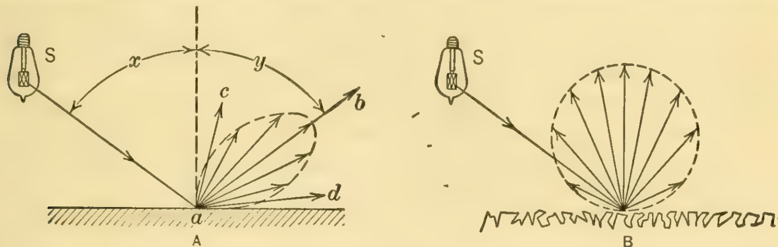


FIG. 90.
A — Reflection from Semi-matte Surface.
B — Reflection from Rough-matte Surface.

owing to cross-reflection from one side to the other and consequent absorption of the light — a condition which is not so likely to obtain in a polished reflector of the same shape. The aluminumized-steel reflector is the only commercial semi-matte reflector in general use.

Rough Matte Surfaces. — If a matte surface is so rough that it has absolutely no sheen, as, for example, the surface of blotting paper (highly magnified, Fig. 90 *B*), and a beam of light strikes it, the light is reflected from the fibers so that when it comes out the rays are sent in all directions. The result is that the whole surface appears equally as bright from one direction as from another. In other words, the candlepower per square inch of apparent area is uniform. White blotting paper is one of the best examples of the diffusing type of reflecting surface; a good sample will reflect about 80 per cent of the light which strikes it.

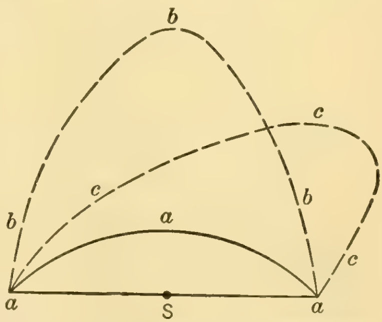


FIG. 91. The Shape of a Rough-surface Reflector has Relatively Little Effect on Distribution.

Since light which falls upon a rough surface is reflected in all directions, it follows that the shape of reflectors using such a surface has little effect on the resulting distribution of light. In Fig. 91, S repre-

sents a light source at the mouth of a rough-surface reflector *aaa*. The light distribution is the same when the reflector is viewed from below; it simply appears as a white disk. However, if a contour such as *bbb* or *ccc* is used rather than *aaa*, there will result a needless absorption of light due to cross-reflection of light between the inside surfaces, and the light from *S* will, therefore, be utilized to better advantage with the shape *aaa*.

Reflectors having a rough reflecting surface are difficult to keep clean and are, therefore, seldom used since, as will be seen later, opal glass and porcelain enamel offer the same advantages.

Prismatic Glassware. Light Control. — Prismatic glassware, as it is usually employed in lighting units, is made up of many small prisms which compose the entire body of the reflector. The principle involved is that of total reflection, which is illustrated in sketch *A* of Fig. 92.

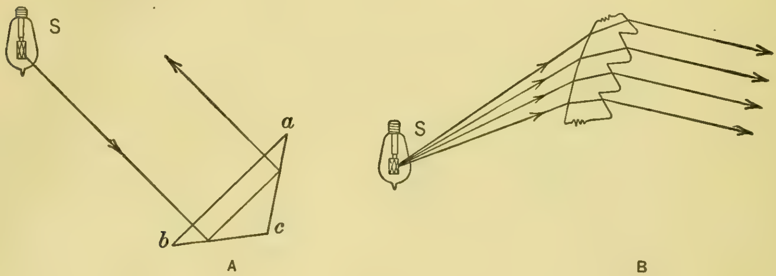


FIG. 92.
A — Reflection by Prism.
B — Refraction by Prisms.

The sketch shows the path of a single light ray; the angles of the prism can be made such that when the light ray passes into it and strikes the back surface, *bc*, it is reflected to the surface, *ac*, and out again as shown. For all practical purposes, this reflection is the same as would be obtained from a polished metal or mirrored surface; that is, each prism is the equivalent of a narrow strip of mirror. By tilting this strip longitudinally, the direction of the reflected beam can be accurately controlled, and by giving it the proper curvature, the desired distribution of all the light falling on it can be obtained. The tops of the prisms are usually rounded slightly, which permits the transmission of a small percentage of the light and thus improves the appearance of the reflector. Prismatic glassware of proper design does not produce striations.

Advantages. — Prismatic glassware suffers no permanent deterioration with age, and since the effect of the prisms is to reinforce the struc-

ture, the strength of the units is high. They are frequently used in preference to steel reflectors in industrial lighting, because the small amount of light transmitted brightens the ceilings and walls and gives the room a more cheerful appearance. Prismatic glassware is also used for refracting or changing the direction of light rays passing through. The prisms used in refractors are of different shape from those used in reflectors. The paths of light rays through four prisms of a refractor are indicated in Fig. 92 *B*. Refractors are commonly used where a very broad distribution of light is desirable, as in the case of street lighting.

Since with both prismatic reflectors and refractors the light is reflected by or passed through clear glass only, the absorption is low and efficiency of such glassware is of the highest order.

Opal Glass. — Opal glass finds considerable application in illumination practice, both as a reflecting and a transmitting medium. In general, there are two types of opal glass, classed as dense and light. The properties of opal glass can be most readily understood if it is

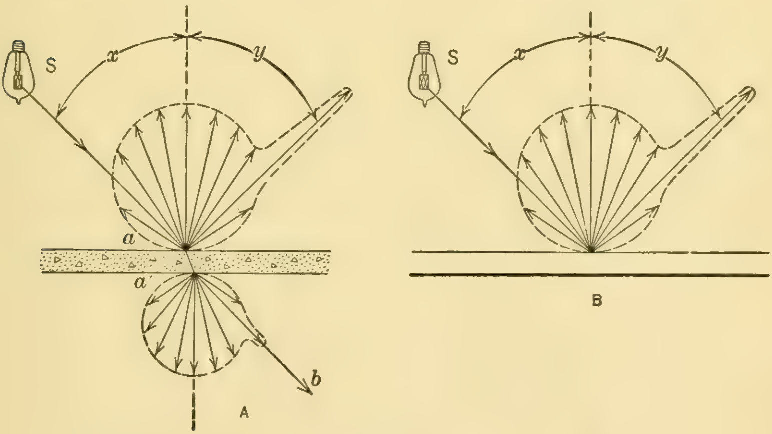


FIG. 93.
A — Reflection and Transmission of Opal Glass.
B — Reflection from Porcelain-enameled Steel.

regarded as common glass in which fine white particles are, so to speak, held in suspension. When a ray of light strikes this surface, part of the light is reflected directly, as in the case of a polished metal surface. The remainder of the light travels through the glass in straight lines until it strikes the white particles, or any minute air bubbles which may be present, whence it is dispersed in all directions, some of it being thrown back and reflected as shown in Fig. 93 and the remainder being transmitted through and out in all directions. If by chance any of the

light passes through the glass and fails to strike any of the white particles, it goes out in a line parallel to the one along which it entered. Thus, if a lamp were enclosed in a ball of opal glass, through which on the average, say, one ray in a hundred could pass without striking any of the white particles, the filament outline would be visible if viewed from the proper direction; in the case of sketch *A* of Fig. 93 this would be in the direction, *ba'*.

The effectiveness of opal glass in redirecting light depends upon the number of white particles and their density in the glass. An opal glass which permits only about 10 per cent of the light striking it to pass through is classed as very dense; light opals may allow as much as 60 per cent to be transmitted. A totally enclosing opal glass ball may, however, have an overall output as high as 80 per cent, for while only 60 per cent of the light coming directly from the lamp to a point on the surface may be transmitted, sufficient light may come to this point from the illuminated interior of the ball to bring the total transmission of the ball up to 80 per cent. For a typical test piece of glass of the common commercial type with 40 per cent transmission, about 20 per cent is absorbed by the glass and the other 40 per cent is reflected in all directions. Dense opal glass need not necessarily be thick. A thin coating of a dense mixture may be "flashed" on a body work of clear glass of ordinary thickness and thus produce what is known as flashed opal.

Porcelain Enamel. — In the familiar enameled metal reflector, the surface, so far as its optical characteristics are concerned, can be considered as a plate of opal glass in optical contact with a steel backing. This opal must be very dense so that as little light as possible will pass through, for all the light that penetrates to the steel backing is absorbed and, therefore, wasted. Enamels vary considerably in efficiency, and if, of two reflectors, one appears gray in comparison with the other, it is sure to be considerably lower in efficiency. Sketch *B*, Fig. 93, shows the characteristic distribution of a porcelain-enameled surface on steel.

Reflectors and Globes

The materials most commonly used for reflectors are porcelain-enameled steel, opal glass, prismatic glass, and mirrored glass. Their commercial applications will now be considered in greater detail.

Porcelain-enameled Steel Reflectors. — The permanence of a porcelain-enameled steel surface, even under unfavorable atmospheric conditions, its moderate cost and the ease with which it can be kept clean have made it the most generally employed among all industrial reflectors. The reflection factor of good-quality porcelain enamel

ranges from 65 to 70 per cent. While this value is not high, it is maintained permanently. Since some porcelain enamel is inferior from the standpoint of reflection factor, care should be exercised in the selection of such reflectors. Any enamel that appears grayish or bluish will be of considerably lower efficiency than one that is white. On the other hand, a slight yellowish cast will show little added absorption where tungsten lamps are used, inasmuch as the yellow rays predominate in the light from these lamps. As previously stated, not more than one-sixth of the light returned from porcelain enamel is regularly reflected as from a mirror; the rest is reflected diffusely, as from a depolished or matte surface, and its distribution is, therefore, independent of the contour of a reflector of given diameter and depth. The degree of control which can be exercised over the distribution of light is, therefore, limited, but is sufficient for most factory lighting requirements. The angle at which the direct light from the lamp is cut off by the reflector and the area of the surface are the characteristics of most importance.

Flat Cone. — The types of porcelain-enameled reflectors commonly employed are illustrated in Figs. 94 to 100. One of the earliest was the flat cone, Fig. 94. For the illumination of interiors, this unit is never to be recommended, since a higher intensity of illumination of better quality can be obtained with other types. The edge of the reflector is at or above the center of the lamp filament; hence, not more than one-half of the light is intercepted and the efficiency of the unit in directing light to the work is of necessity low. Much of the light of the lamp is emitted at or near the horizontal and, striking high on the walls of the room, is to a large extent wasted. No shielding of the bright filament of the lamp is afforded; hence, the glare will be pronounced except where the units are used in very high bays and there the waste of light is very great. Where lamps are suspended lower, even those with frosted bulbs will be glaring. That proportion of the total light which is received from the reflector is insufficient to soften shadows appreciably.

FIG. 94. Flat Cone.

Deep or Bowl Reflector. — The deep, or bowl reflector, illustrated in Fig. 95, has been largely employed to give maximum shielding of the lamp filament. The mistake is frequently made of assuming that since this reflector intercepts more light than other types, it is the most efficient in directing light to the work. On the contrary, the output of typical bowl reflectors is only 65 per cent. The candlepower below the

unit is at no angle materially greater than for the dome (Figs. 96 and 97), because of the losses resulting from cross-reflection in the reflector; and at the higher angles the intensity is considerably reduced. Surfaces above the general level of the work are frequently inadequately lighted with such units, and a room with dark-toned walls is likely to appear dingy. While the deep reflector does shield the eye from the direct glare of the filament, it does not in any way modify the brightness of the filament images reflected from polished surfaces. Furthermore, the

Fig. 95. Bowl.

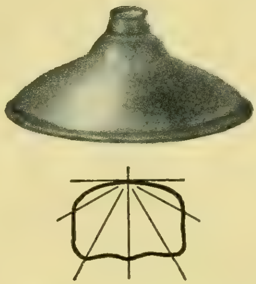


Fig. 96. Old Dome.

Fig. 97. R L M Dome.

surface from which the light is received is so small that shadows are sharp and may prove annoying. Diffusion of the light coming directly from the lamp is, therefore, important. The bowl-enameled lamp produces the desired diffusion and is very successful when used with a reflector of greater diameter. However, it is not so desirable with the bowl reflector inasmuch as the output of the unit suffers too great a loss. The field for the most advantageous use of bowl reflectors is for somewhat localized illumination over benches and tables where the units are hung low.

Dome Shape. — The dome shape, Fig. 96, a mean between the flat and bowl types, became the standard for the majority of installations of vacuum tungsten lamps and steel reflectors. The output of typical reflectors is 75 to 80 per cent of the light generated by the lamp; the percentage of light utilization is as high as with any enameled unit. Experience shows that under most conditions the eye is sufficiently shielded from glare when vacuum tungsten lamps are employed; yet enough light is emitted at the higher angles to illuminate higher vertical and oblique surfaces properly. The large area of the reflector provides a source of illumination which tends to minimize the harshness of shadows.

R L M Dome. — However, with gas-filled tungsten lamps in these reflectors, the greater brightness of the filament makes added protection

from glare desirable. Furthermore, this lamp, with its concentrated filament, makes it possible to achieve a more nearly ideal reflector design than was possible with vacuum lamps. After a thorough study of the requirements, a standard design was evolved which virtually combined the advantages of the older dome and bowl types. The angle of cut-off, Fig. 98, was made somewhat lower than in the old form of dome and this gave the required added protection from direct glare without appreciably sacrificing effectiveness of illumination. The new reflector is known as the R L M (Reflector and Lamp Manufacturers') Standard dome. With this unit available, the field for the bowl reflector becomes much restricted. The general lighting of a plant can be done more effectively with the R L M dome in almost every case.

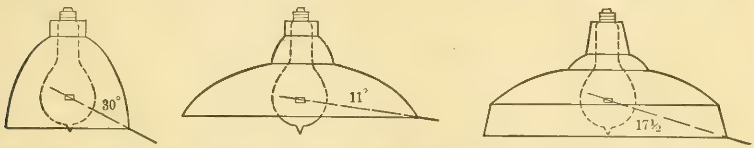


FIG. 98. Angle of Cut-off for Bowl, Old Dome and R L M Dome Reflectors.

Not only the angle of cut-off, but all other factors which affect the performance of a porcelain-enameled reflector have been considered in the design of the R L M Standard. The minimum diameter for each size of lamp, the light distribution, and the reflection factor of the surface are all specified.

Use of Clear-Bulb Lamps. — Ordinarily, clear-bulb tungsten lamps should not be used with dome reflectors at mounting heights of less than 20 feet. Above this height the nearest lamp within the usual field of vision is so far removed that ordinarily the amount of light entering the eye directly from it is insufficient to cause glare; also, the lighting unit subtends so small an angle at the working surface that shadows are not greatly softened by obscuring the lamp bulbs. When suspended nearer the floor, the lamps should be of the bowl-enameled type. The output of the units is then approximately 65 per cent.

Reflecting Band. — Various equipments are available combining a flat reflector with a metal reflecting band suspended so as to shield the eye from the direct view of the filament. They accomplish a desirable protection against direct glare, inasmuch as the direct light is cut off at an angle fully as low or lower than with the bowl type of reflector. They are not, however, designed to reduce the brilliancy of specular images of the lamp filament in the working surfaces, which so frequently cause the most annoying glare. The diffusion of light is not so great

as one might assume from the dimensions of the fixture, for the light is actually in large measure localized to the lamp and the small reflecting band. The upper reflector contributes only a small part of the illumination. The use of the reflecting shield may be justified as an emergency measure in connection with existing installations of flat-cone reflectors, but new installations of flat, shallow reflectors with reflecting shields are not to be recommended.

Angle Type. — The angle type of reflector shown in Fig. 99 also finds some application in industrial plants. When these reflectors are employed for the general illumination of a shop, they should be attached to the walls or columns between bays and should be suspended not less than 20 feet above the floor; otherwise glare will be excessive when the workmen face in the direction of the units. The illumination of vertical surfaces is, of course, relatively high with such equipment. Most angle units emit a high intensity near the horizontal and, therefore, waste a considerable portion of the light, besides accentuating glare. For bill-board or sign-lighting service, in which many of these reflectors are applied, the distribution of light is favorable. In industrial plants, however, the design shown in Fig. 100, shading the lamp more perfectly and directing the light downward and with greater spread, often has marked advantages. In general, to secure satisfactory distribution of light, angle reflectors must be combined with overhead units; the exception would be an interior which is very narrow in relation to its height.

Fig. 99. Angle Type.

Paint-enameled Steel Reflectors. — While porcelain enamel has become the standard surface for metal reflectors, paint-enameled and aluminumized units are used to a limited extent. The best paint enamel has the advantage of a slightly higher initial efficiency and lower cost, but both these and aluminumized reflectors show marked deterioration after being in service two or three years. Hence the use of such reflectors will be found economical only in installations of a temporary character.

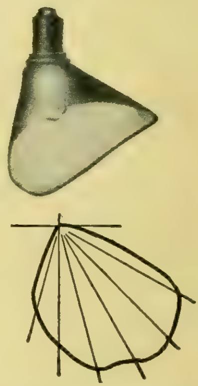


Fig. 100. Another Angle Type.

Opal-glass Reflectors and Globes. — Since an opal-glass surface reflects light diffusely in about the same manner as does porcelain enamel, it is not suited for use where a concentrated or otherwise accurately

controlled distribution is desired. In addition to that reflected, some of the light from the lamp which would be absorbed in a steel reflector is transmitted through the glass. The total output from opal-glass reflectors varies from 75 to 85 per cent of which from 10 to 35 per cent is in the upper hemisphere, depending upon the density of the glass. Opal units are available in various contours or types. The bowl type, Fig. 101, has usually been employed. The light transmitted through the reflector assists in the illumination of vertical and oblique surfaces sufficiently to produce results appreciably better than those obtained with the bowl type of enameled-steel units — in fact, the illumination results are more nearly comparable with those from the dome type. Since the reflectors are of relatively small diameter, shadows are sharp when ceilings and walls are dark; however, where these surfaces are of light finish, much of the transmitted light is reflected back to the work and illuminates the shadows, besides adding to the efficiency of light utilization and rendering the appearance of the plant more attractive and stimulating.

Fig. 101. Opal Glass Reflector.

Glass Steel. — Recently a combination glass and steel reflector has been designed which retains the principal advantages of the porcelain-enamel unit together with a small component of upward light to illuminate the walls and ceiling.

Glass reflectors are particularly effective where favorable wall and ceiling conditions exist, and under these conditions the efficiency of an installation of light-density opal reflectors is only slightly less than for the bowl-type steel, and about 20 per cent less than that of an installation of steel domes under the same conditions. With dense opal-glass units the percentage of light utilization is of the same order as with the steel dome reflectors. The protection from glare is also better than with the light-density glass. The dense opal reflector is, therefore, to be preferred in practically all cases.

Mechanical Strength. — Opal or milk-glass is never as strong mechanically as clear glass and no glass reflectors are suited for use when hung low on drop cords. On the other hand, in plants where they have been installed for overhead lighting in locations where they are reasonably free from being shattered by mechanical blows, the breakage has not assumed objectionable proportions.

Bowl-enameled gas-filled tungsten lamps should be employed with glass reflectors which are suspended less than 20 feet above the floor.

Glass Enclosing Units. — With opal enclosing globes, of glass which is even in density and thickness so that the globe is uniformly luminous, the candlepower in any direction varies directly with the projected area viewed in that direction. A ball globe of this kind will, therefore, give equal candlepower in all directions except at those few angles where the projected area is reduced by the fixture which supports the globe.

A long globe or stalactite, for like reason, gives a maximum candlepower in the horizontal direction and less beneath the unit. Likewise a globe such as that shown in Fig. 102*a* gives its maximum candlepower in the vertical directions and its minimum in the horizontal direction.

Fig. 102*a*. Glass Enclosing Unit, Flattened Reflecting Top.

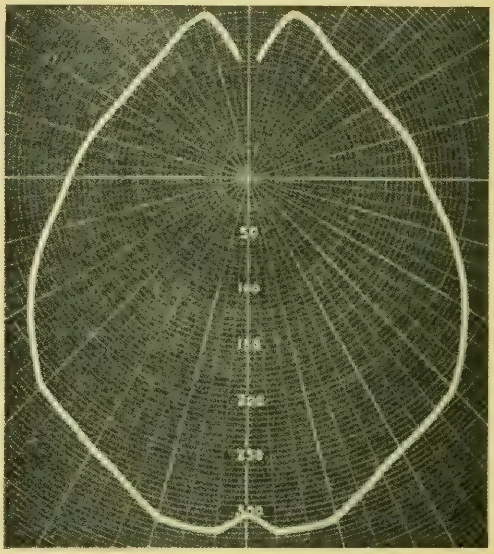


Fig. 102*b*. Photometric Distribution Curve of Unit Illustrated in Fig. 102*a*.

Furthermore, with globes of this character it has been found possible to have the upper portion near the holder relatively thick, thus making it more of a reflector. A curve such as that shown in Fig. 102*b* is thus obtained. Obviously, enclosing globes such as these are much more efficient lighting units than the ordinary ball globes.

Diffusing globes, with or without external reflectors, give a pleasing appearance of brightness to the walls and ceiling of a room and also provide an excellent illumination of work in vertical or oblique planes. The wattages ordinarily employed for a given size of globe should be such that the brightness is not above the value which can be viewed with comfort and without interference with vision.

Semi-enclosing Units. — A source of low brightness and large area may be obtained in a class of "semi-enclosing" units, so-called because some of the rays may emerge from the unit without first passing through the diffusing glass. They consist of a diffusing glass bowl suspended beneath the lamp, above which is placed either an opaque reflector or one of dense opal glass. This upper reflecting surface is made large in order to produce added diffusion. The space between the lower bowl and upper reflector is sometimes left open, or it may be enclosed with clear glass. Again, the unit may be in one piece with a coating of enamel placed on the outside of the upper reflector and of the lower bowl, as in Fig. 103. To be most satisfactory, fixtures of this type should have a bowl of considerable density so that the brightness may not be excessive. Those units with the greatest number of the light-transmitting or reflecting surfaces exposed to dust accumulation will show the most rapid depreciation in service.

Fig. 103. Semi-enclosing Unit and Reflector.

Semi-indirect Bowls. — With semi-indirect systems, the ceiling is used as the upper reflector and illumination is received from a larger surface than with any of the equipments previously discussed. If a dense opal bowl is employed the brightness of the glass is of the same order as that of a light-finished ceiling above it and the maximum softness of shadows is secured. Light-density opal glass should be used for semi-indirect lighting with bowls of large dimensions only, so as to secure low brightness with consequent freedom from glare. However, this leads to higher cost than when a unit of dense opal glass and of smaller dimensions, such as shown in Fig. 104, is employed. Semi-indirect lighting is not considered practicable in factories except where ceilings may be finished light and can be kept fairly clean, where there are few obstructions near the ceiling, and where there is little dust or dirt to settle in the bowls. The effect of the last factor may be reduced by providing conical covers of clear glass. (See Fig. 105.) A combination of indirect lighting with a small component of direct is likewise obtained in a type of unit consisting of an inverted enameled-metal reflector with an open bottom, a short distance below which is suspended a diffusing glass plate of somewhat greater diameter, as indicated in Fig. 106. The small amount of light reflected upward from near the

rim of the plate serves to illuminate the outer surface of the opaque reflector to an acceptable brightness. Characteristic of this type of unit is a distribution curve with practically no intensity at angles close to the horizontal. With a diffusing plate of light density the brightness of the plate will be as high as that of light-density semi-indirect units,

FIG. 104. Semi-indirect Unit.

FIG. 105. Semi-indirect Glass Unit Enclosed with Glass Top.

FIG. 106. Inverted Enameled Unit.

but a flat plate of this character will not prove annoying from the standpoint of direct glare.

Prismatic-glass Reflectors. — Prismatic-glass reflectors, Fig. 107, may be designed to redirect the light with small absorption, and the properties of the prisms will suffer no deterioration with age. In practice, typical units are made to transmit about 15 to 20 per cent above the horizontal and to direct downward 65 to 75 per cent of the light from the lamp. As in the case of mirrored-glass reflectors, prismatic units may be designed to give any desired control of light distribution. Where a strongly concentrated distribution of light is required, it can be secured accurately and efficiently with prismatic units; also it is possible to control the wider distributions so as to illuminate vertical surfaces to a relatively higher intensity than with enameled-steel or opal-glass reflectors. Because of the deep valleys

between ridges of the prisms, more labor is required in cleaning these reflectors than those with smooth surfaces. Loose dust on the outside of the reflector merely reduces the light transmitted to the ceiling, but grime and dirt in optical contact with the prisms nullify their reflecting properties and seriously impair the efficiency of the unit. With prismatic reflectors, unless frosted, shadows are sharp, as with mirrored units, and on account of the bright specular images of the reflector they are not well adapted for use above polished surfaces.

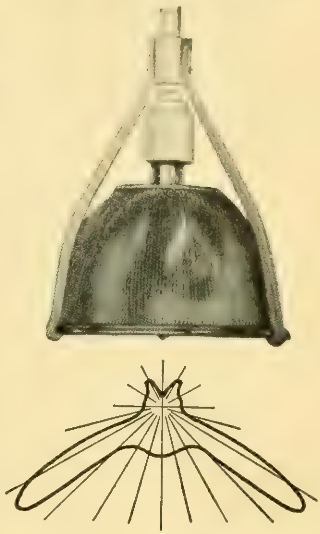


FIG. 107. Prismatic Glass Reflector.

Prismatic and mirror-glass reflectors and prismatic-glass refractors especially designed for show-window lighting and street lighting are discussed in detail in the chapters devoted to these subjects.

Mirrored-glass Reflectors. — Mirrored glass has a higher reflection factor than any other surface used in industrial reflectors. In a reflector of high quality this efficiency is maintained permanently and the direction of the light can be controlled accurately since the reflection is almost entirely regular and not diffuse. Such regular reflection of the light, if unmodified, would, however, lead to striations or images of the filament on illuminated surfaces. To avoid these the reflector is usually corrugated (Fig. 108). Images of the lamp filament as seen in the reflector are nearly as bright as the filament itself; hence a reflector of a contour similar to a porcelain-enameled dome would be exceedingly troublesome from this standpoint. It is good practice, therefore, to use only the deeper designs in a mirrored-glass reflector. This necessarily limits the intensity at higher angles. It tends, also, to leave sharp shadows. From the standpoint of glare from polished working surfaces, a mirrored-glass unit, even when equipped with a bowl-frosted lamp, evidently is at a disadvantage inasmuch as the reflector surfaces within certain angles are only slightly less bright than the lamp filament itself. The output of typical units varies from 60 to

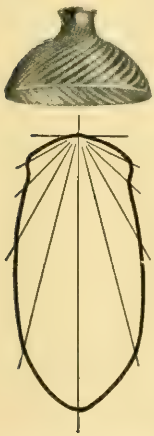


FIG. 108. Mirrored Glass Reflector.

85 per cent, depending upon the degree of light control exercised. Their best application is in high bays.

Totally Indirect Lighting. — With totally indirect lighting (Fig. 109), the maximum diffusion of light is secured, but here again, as with semi-indirect lighting with dense bowls, the shadows may be so suppressed that, in some cases, the perception of objects in their three dimensions is less satisfactory than with direct lighting units. Since the net efficiency of light utilization is at best well below that obtained with well-designed direct lighting, it is particularly important that the surface of the reflector be of the highest efficiency; mirrored-glass units are, therefore, widely employed for this service.

FIG. 109. Totally Indirect Unit.

Characteristics of Lighting Systems

Illumination Levels. — The eye is capable of adapting itself to see under illumination levels which range from a small fraction of a foot-candle to several thousand foot-candles in value. At very low intensities the eye does not receive sufficient light to enable it to distinguish color or detail, and at very high values a blinding effect is experienced which also obliterates detail. Between these limits there is a wide range within which good vision is possible. Considerations of economy usually limit the intensities employed in artificial lighting to the lower values of this range. So closely is the lower limit approached that it is necessary in designing a lighting installation to take into consideration such factors as the color of the objects requiring illumination, since objects are seen by the light which they reflect and dark objects require more than light ones for equally good vision; the order of brightness of surroundings, the amount which it is considered expedient to apportion for the advertising value of good illumination and the intricacy of the work which is performed under the artificial lighting. For example, a jewelry store in a small town may be brightly lighted at an intensity of 6 foot-candles, whereas a jewelry store located on a prominent business street in a large city will require, to be considered well lighted, perhaps 8 to 10 foot-candles.

Foot-candle Values. — Again, the cloak and suit department of a large store will require a higher level of illumination than will the white-goods department. An industrial plant engaged in rough-box manufacture would be well lighted at 5 foot-candles; in a high-grade machine

shop as much as 12 foot-candles would be desirable. The range of values given in Table XXXII has been established by experience and used by various authorities in current practice. Bearing in mind the character of the work, the fineness of detail to be observed, and the standard of lighting of the immediate surroundings, one should be able to select a suitable value from this table to serve as a basis for illumination calculations. It should be remembered, however, that the amount so chosen can rarely be exactly provided in practice.

The foot-candle values listed in the following table correspond to present standards for different classes of industrial operations, for offices, stores, etc. It should be remembered that the standards of lighting have been steadily increasing with improvement in lamps and equipment and lowered costs for power, so that the higher values given are, in general, the most desirable, not only from the standpoint of visual requirements but from the standpoint of provision for the future.

TABLE XXXII

PRESENT STANDARDS OF FOOT-CANDLE ILLUMINATION FOR STORES, COMMERCIAL AND PUBLIC INTERIORS

	Foot-candles	
	Recommended	Under Some Conditions
Department Stores and Large Specialty Stores		
Main Floors	10	6–12
Basement Store	10	6–12
Other Floors	8	5–10
Show Windows	..	10–100
Stores of Medium Size		
Clothing, Dry Goods, Furniture, Etc.	8	5–10
Exclusive Small Stores		
Light Goods	8	5–10
Dark Goods	12	8–16
Small Stores		
Art	8	5–10
Automobile Supply	6	4–8
Bake Shop	6	4–8
Book	6	4–8
China	6	4–8
Cigar	8	5–10
Clothing	8	6–12
Confectionery	8	5–10
Dairy Products	8	5–10
Decorator	8	5–10
Drug	8	5–10
Dry Goods	8	5–10
Electrical Supply	8	5–10
Florist	6	4–8
Furrier	8	5–10
Grocery	8	5–10
Haberdashery	8	6–12
Hardware	6	4–8
Hat	8	6–12
Jewelry	8	5–10
Leather, Handbags and Trunks	6	4–8
Meat	8	5–10
Millinery	8	5–10
Music	6	4–8
Notions	6	4–8
Piano	6	4–8
Shoe	8	6–12
Sporting Goods	6	4–8
Tailor	8	6–12
Tobacco	8	5–10
Variety Store	10	6–12
Armories, Public Halls	5	3–6
Auditoriums	3	2–4
Automobile Show Room	8	6–12
Bank		
Lobby	6	4–8
Cages and Offices	10	6–12
Barber Shop	8	6–12

TABLE XXXII

PRESENT STANDARDS OF FOOT-CANDLE ILLUMINATION FOR STORES, COMMERCIAL AND PUBLIC INTERIORS. — *Continued*

	Foot-candles	
	Recommended	Under Some Conditions
Cars		
Baggage	6	5–10
Daycoach, Subway	8	6–12
Dining	8	6–12
Mail	10	6–12
Pullman	8	6–12
Street Ry	8	6–12
Churches		
Auditorium	3	2–4
Sunday School Room	5	3–6
Club Rooms	4	3–6
Dance Halls	4	3–6
Dental Office		
Waiting Room	4	3–6
Office	15	10–20
Depot — Waiting	4	3–6
Drafting Room	15	10–20
Elevators — Freight and Passenger	4	3–6
Gymnasiums		
Main Exercising Floor	8	5–10
Swimming Pool	4	3–6
Shower Rooms	4	3–6
Locker Rooms	4	3–6
Fencing, Boxing, Wrestling	8	5–10
Halls, Passageways in Interiors	2	1–4
Hospitals		
Lobby and Reception Room	4	3–6
Corridors	3	2–4
Wards and Private Rooms:		
With local illumination	3	2–4
With no local illumination	6	4–8
Night illumination	0.1	0.1–0.2
Operating Table	75	50–100
Operating Room	10	6–12
Laboratories	10	6–12
Hotels		
Lobby	4	3–6
Dining Room	5	4–8
Kitchen	6	5–10
Bedrooms	6	4–8
Corridors	1	1–2
Writing Room	8	5–10
Indoor Recreations		
Basketball and Indoor Baseball	10	6–12
Bowling (On Alley, Runway and Seats)	5	3–6
(On Pins)	15	10–20
Billiards (General)	4	3–6
(On Table)	15	10–20
Racquet, Handball, Squash and Indoor Tennis	15	10–20
Skating Rinks	5	4–8

TABLE XXXII

Present Standards of Foot-candle Illumination for Stores, Commercial and Public Interiors. — *Continued*

	Foot-candles	
	Recommended	Under Some Conditions
Library		
Reading Room	8	5–10
Stack Room	4	3–6
Lodge Rooms	4	3–6
Lunch Room	8	5–10
Market	8	5–10
Moving Picture Theatre		
During Intermission	3	2–4
During Pictures	0.1	0.1–0.2
Museum (General)	5	4–8
(On Walls)	8	5–10
Office Buildings		
General Offices	10	6–12
Private Offices	10	6–12
File Room	4	3–6
Stenographer and Bookkeeping Rooms	10	6–12
Vault	4	3–6
Restaurants	5	4–8
Schools		
Auditorium	5	4–8
Class Rooms, Library and Office	8	5–10
Corridors and Stairways	3	2–4
Drawing	15	10–20
Laboratories	10	6–12
Manual Training	10	6–12
Sewing Rooms	15	10–20
Study Room		
Desks	8	5–10
Blackboards	6	4–8
Studio		
Art and Photographic	10	6–12
Moving Picture		
General	5	3–6
Sets (Photographic Daylight)	..	500–2000
Telephone		
Manual Exchanges	5	3–6
Automatic Exchanges	10	6–12
Theatres		
Auditorium	4	3–6
Foyer	5	3–6
Lobby	8	5–10
Toilet and Washrooms	5	3–6

Industrial

Office		
Private, General	10	6–12
Drafting Room	15	10–20

TABLE XXXII

Present Standards of Foot-candle Illumination for Stores, Commercial and Public Interiors. — *Continued*

	Foot-candles	
	Recommended	Under Some Conditions
Industrial		
Aisles, Stairways, Passageways and Corridors	2	1–2
Assembling		
Rough	5	3–6
Medium	8	5–10
Fine	10	6–12
Extra Fine	10–50	.....
Bakeries	8	5–10
Boilers, Engine Rooms and Power Houses		
Boilers, Coal and Ash Handling, Storage Battery Rooms	3	2–4
Auxiliary Equipment, Oil Switches and Transformers	5	3–6
Switch Boards, Engines, Generators, Blowers, Compressors	6	4–8
Candy Making	8	5–10
Canning and Preserving	8	5–10
Chemical Works		
Hand Furnaces, Boiling Tanks, Stationary Driers, Stationary or Gravity Crystallizing	3	2–4
Mechanical Furnaces, Generators and Stills, Mechanical Driers, Evaporators, Filtration, Mechanical Crystallizing, Bleaching	4	3–6
Tanks for Cooking, Extractors, Percolators, Nitrators, Electrolytic Cells	6	4–8
Clay Products and Cements		
Grinding, Filter Presses, Kiln Rooms	3	2–4
Molding, Pressing, Cleaning and Trimming	5	3–6
Enameling	6	4–8
Coloring and Glazing	10	6–12
Cloth Products		
Light Goods	10	6–12
Dark Goods	10–50	10–50
Dairy Products	8	5–10
Electric Manufacturing		
Storage Battery, Molding of Grids	6	4–8
Coil and Armature Winding, Mica Working, Insulating Processes	10	8–16
Elevator, Freight and Passenger	5	3–6
Forge Shops and Welding		
Rough Forging	6	4–8
Fine Forging and Welding	10	6–12
Foundries		
Charging Floor, Tumbling, Cleaning, Pouring and Shaking Out	5	3–6
Rough Molding and Core Making	6	4–8
Fine Molding and Core Making	10	6–12

TABLE XXXII

PRESENT STANDARDS OF FOOT-CANDLE ILLUMINATION FOR STORES, COMMERCIAL AND PUBLIC INTERIORS. — *Continued*

	Foot-candles	
	Recommended	Under Some Conditions
Glass Works		
Mix and Furnace Rooms, Casting and Lehr	6	4–8
Grinding, Glass Blowing Machines, Cutting Glass to Size, Silvering	8	5–10
Fine Grinding, Polishing, Beveling, Inspecting, Etching and Decorating	10	6–12
Glass Cutting (cut glass), Inspecting fine	10–50	....
Glove Manufacturing		
Light Goods		
Cutting, Pressing, Knitting	8	5–10
Sorting, Stitching, Trimming and Inspecting	10	8–16
Dark Goods		
Cutting, Pressing, Knitting	10	6–12
Sorting, Stitching, Trimming and Inspecting	10–50	....
Hat Manufacturing		
Dyeing, Stiffening, Braiding, Cleaning and Refining		
Light	6	4–8
Dark	10	6–12
Forming, Sizing, Pouncing, Flanging, Finishing, Ironing		
Light	8	5–10
Dark	10	6–12
Sewing		
Light	10	6–12
Dark	10–50	....
Ice Making		
Engine and Compressor Room	6	4–8
Inspecting		
Rough	6	4–8
Medium	10	6–12
Fine	15	10–20
Extra Fine	10–50	....
Jewelry and Watch Manufacturing	10–50	....
Laundries and Dry Cleaning	8	5–10
Leather Manufacturing		
Vats	3	2–4
Cleaning, Tanning and Stretching	4	3–6
Cutting, Fleshing and Stuffing	6	4–8
Finishing and Scarfing	10	6–12
Leather Working		
Pressing and Winding		
Light	8	5–10
Dark	10	6–12
Grading, Matching, Cutting, Scarfing, Sewing		
Light	10	8–16
Dark	10–50	....
Locker Rooms	4	2–4

TABLE XXXII

Present Standards of Foot-candle Illumination for Stores, Commercial and Public Interiors. — *Continued*

	Foot-candles	
	Recommended	Under Some Conditions
Machine Shops		
Rough Bench and Machine Work	6	4–8
Medium Bench and Machine Work, Ordinary Automatic Machines, Rough Grinding, Medium Buffing and Polishing	10	6–12
Fine Bench and Machine Work, Fine Automatic Machines, Medium Grinding, Fine Buffing and Polishing	12	8–16
Extra Fine Bench and Machine Work, Grinding (fine work)	10–50	....
Meat Packing		
Slaughtering	5	3–6
Cleaning, Cutting, Cooking, Grinding, Canning, Packing	8	5–10
Milling and Grain Foods		
Cleaning, Grinding or Rolling	5	3–6
Baking or Roasting	8	5–10
Packing		
Rough	4	3–6
Medium	6	4–8
Fine	10	6–12
Paint Manufacturing	6	4–8
Paint Shops		
Dipping, Spraying, Firing	5	3–6
Rubbing, Ordinary Hand Painting and Finishing	8	5–10
Fine Hand Painting and Finishing	10	8–16
Extra Fine Hand Painting and Finishing (Automobile Bodies, Piano Cases, etc.)	15	10–50
Paper Box Manufacturing		
Light	6	4–8
Dark	8	5–10
Paper Manufacturing		
Beaters, Machine, Grinding	4	3–6
Calendering	6	4–8
Finishing, Cutting and Trimming	8	6–12
Plating	5	3–6
Polishing and Burnishing	8	6–12
Printing Industries		
Matrixing and Casting, Miscellaneous Machines, Presses	8	5–10
Proof Reading, Lithographing, Electrotyping	10	6–12
Linotype, Monotype, Typesetting, Imposing Stone, Engraving	10–50	....
Receiving and Shipping	4	3–6
Rubber Manufacturing and Products		
Calenders, Compounding Mills, Fabric Preparation, Stock Cutting, Tubing Machines, Solid Tire Operations, Mechanical Goods Building, Vulcanizing	8	5–10
Bead Building, Pneumatic Tire Building and Finishing, Inner Tube Operation, Mechanical Goods Trimming, Treading	10	6–12

TABLE XXXII

PRESENT STANDARDS OF FOOT-CANDLE ILLUMINATION FOR STORES, COMMERCIAL AND PUBLIC INTERIORS. — *Concluded*

	Foot-candles	
	Recommended	Under Some Conditions
Sheet Metal Works		
Miscellaneous Machines, Ordinary Bench Work	8	5–10
Punches, Presses, Shears, Stamps, Welders, Spinning, Fine Bench Work	10	8–16
Shoe Manufacturing		
Hand Turning, Miscellaneous Bench and Machine Work	8	5–10
Inspecting and Sorting Raw Material, Cutting, Lasting and Welding (light)	10	6–12
Inspecting and Sorting Raw Material, Cutting, Stitching (dark)	10–50	....
Soap Manufacturing		
Kettle Houses, Cutting, Soap Chip and Powder	5	3–6
Stamping, Wrapping and Packing, Filling and Packing Soap Powder	6	4–8
Steel and Iron Mills, Bar, Sheet and Wire Products		
Soaking Pits and Reheating Furnaces	2	1–3
Charging and Casting Floors	4	3–6
Muck and Heavy Rolling, Shearing, rough by gauge, Pickling and Cleaning	5	3–6
Automatic Machines, Rod, Light and Cold Rolling, Wire Drawing, Shearing, fine by line	8	5–10
Store and Stock Rooms		
Rough	3	2–4
Medium	6	4–8
Fine	8	5–10
Structural Steel Fabrication	6	4–8
Textile Mills		
(Cotton)		
Opening and Lapping, Carding, Drawing Frame, Roving, Dyeing	5	3–6
Spooling, Spinning, Drawing In, Warping, Weaving, Quilling, Inspecting, Knitting, Slashing	8	5–10
(Silk)		
Winding, Throwing, Dyeing	12	8–16
Quilling, Warping, Weaving and Finishing		
Light Goods	8	5–10
Dark Goods	10	8–16
(Woolen)		
Carding, Picking, Washing and Combing	4	3–6
Twisting and Dyeing	6	4–8
Drawing In, Warping		
Light Goods	6	4–8
Dark Goods	10	8–16
Weaving		
Light Goods	8	5–10
Dark Goods	12	10–20
Knitting Machines	10	6–12
Tobacco Products	8	5–10
Toilet and Wash Rooms	4	3–6
Wood Working		
Rough Sawing and Bench Work	5	3–6
Sizing, Planing, Rough Sanding, Medium Machine and Bench Work, Gluing, Veneering, Cooperage	8	5–10
Fine and Bench and Machine Working, Fine Sanding and Finishing	10	6–12

Illumination of Vertical Surfaces. — For many locations, such as offices and drafting rooms, light is required principally on horizontal planes, such as desk tops or table tops, and for these it has been the custom, and not altogether an improper one, to calculate illumination on the basis of that delivered to horizontal surfaces with the assumption that the oblique surfaces of objects would be sufficiently lighted. This practice may result in inadequate illumination. In a machine shop, for example, the lighting of the vertical surfaces of the work or of machine parts is fully as important as the lighting of the horizontal surfaces. As a matter of fact, most shops are lighted during the day only by light from windows which give a greater light on the vertical surfaces than on the horizontal. In all such cases where direct lighting is used, only those lighting units should be installed which show a reasonably good candlepower in the 50–70 degree zone as well as below these angles. To cite an extreme case, a shop lighted by closely spaced automobile headlights directing the light downward from the ceiling would furnish ample light on a horizontal plane but such lighting would be far from satisfactory. In Table XXXIII lighting units are compared on their relative vertical and horizontal bases.

Diffusion of Light. — In addition to a knowledge of reflecting surfaces and reflectors, a knowledge of such other factors as glare, shadow, and illumination of vertical surfaces — in a word, the diffusion of light — is necessary before an intelligent selection of a lighting system can be made. These factors all require most careful consideration if the best results are to be obtained.

Glare. — By "glare" is meant any brightness within the field of vision of such a character as to cause discomfort, annoyance, interference with vision, or eye fatigue. Always a hindrance to vision, it often, like smoke from a chimney, represents a positive waste of energy as well. Hence, it has sometimes been characterized as light out of place. It is one of the faults most commonly found in all lighting installations.

Avoidance of Glare.[1] — "Glare is objectionable because (1) when continued it tends to injure the eye and to disturb the nervous system; (2) it causes discomfort and fatigue and thus reduces the efficiency of the worker; and (3) it interferes with clear vision, and thus reduces the efficiency and in many cases increases the risk of accident or injury to the worker. From both a humanitarian and a business viewpoint, the owner or operator of a factory should be interested in avoiding glare, whether caused by daylight or by artificial light. On the other

[1] From Code of Lighting Factories, Mills and Other Work Places — prepared by the U. S. Illuminating Engineering Society.

TABLE XXXIII

A GUIDE TO THE SELECTION OF REFLECTING EQUIPMENT

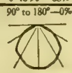
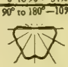
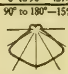
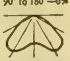
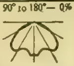
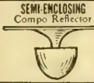
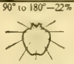
	LIGHTING UNIT		EFFICIENCY BASED UPON		FAVORABLE APPEARANCE OF LIGHTED ROOM	DIRECT GLARE	REFLECTED GLARE	SHADOWS	MAINTENANCE
			ILLUMINATION ON HORIZONTAL	ILLUMINATION ON VERTICAL					
	DIRECT LIGHTING PORCELAIN ENAMEL REFLECTORS								
1	R L M DOME  Clear Lamp	90° to 180°—0%  0° to 90°—76%	A+	B+	C+	C	D	C+	A+
2	R L M DOME Bowl-Enameled Lamp	90° to 180°—0%  0° to 90°—66%	A−	B	B	B+	B	B+	A−
3	GLASSTEEL DIFFUSER 	90° to 180°—7%  0° to 90°—60%	B+	B	A−	A−	B+	A−	B+
4	DEEP BOWL  Clear Lamp	90° to 180°—0%  0° to 90°—65%	B+	B−	C	C+	D	C	A
5	DEEP BOWL Bowl-Enameled Lamp	90° to 180°—0%  0° to 90°—58%	B	C+	C	B	C+	C+	B+
6	FLAT CONE Shielding Band  Clear Lamp	90° to 180°—1%  0° to 90°—54%	B	C+	C+	C+	D	C	B+
7	FLAT CONE  Clear Lamp	90° to 180°—10%  0° to 90°—74%	B	B	C	D	D	C	A+
	DIRECT LIGHTING OPEN GLASS REFLECTORS								
8	LIGHT DENSITY OPAL  Clear Lamp	90° to 180°—33%  0° to 90°—54%	B+	B	B+	C+	D	B−	B
9	LIGHT DENSITY OPAL Bowl-Enameled Lamp	90° to 180°—36%  0° to 90°—45%	B	B−	A−	B−	B−	B+	B−
10	DENSE OPAL  Clear Lamp	90° to 180°—15%  0° to 90°—67%	A+	B+	B+	B	D	C+	A−
11	DENSE OPAL Bowl-Enameled Lamp	90° to 180°—16%  0° to 90°—60%	B+	B−	A−	B+	B−	B	B
12	MIRRORED GLASS  Clear Lamp	90° to 180°—0%  0° to 90°—68%	A	B	C	C+	D	C	A−
13	MIRRORED GLASS Bowl-Enameled Lamp	90° to 180°—0%  0° to 90°—55%	B	C+	C	B−	C	C+	B−
14	PRISMATIC INDUSTRIAL  Clear Lamp	90° to 180°—18%  0° to 90°—73%	A+	A−	B+	C+	D	C+	B−

TABLE XXXIII. — *Concluded*

A GUIDE TO THE SELECTION OF REFLECTING EQUIPMENT									
LIGHTING UNIT			EFFICIENCY BASED UPON		FAVORABLE APPEARANCE OF LIGHTED ROOM	DIRECT GLARE	REFLECTED GLARE	SHADOWS	MAINTENANCE
			ILLUMINATION ON HORIZONTAL	ILLUMINATION ON VERTICAL					
DIRECT LIGHTING ENCLOSING AND SEMI-ENCLOSING UNITS									
15	DIFFUSING GLOBE Light Opal 	90° to 180°—35%  0° to 90°—40%	B–	B–	A	B–	B	B+	B+
16	ONE-PIECE OPAL Flattened Reflecting Top 	90° to 180°—35%  0° to 90°—45%	B	B	A	B	B	A–	A–
17	PRISMATIC ENCLOSING 	90° to 180°—27  0° to 90°—59%	B+	B	A	B	B–	B+	B
18	SEMI-ENCLOSING Metal Reflector 	90° to 180°—20%  0° to 90°—56%	B	B	A	B	B	B+	B–
19	SEMI-ENCLOSING Compo Reflector 	90° to 180°—13%  0° to 90°—60%	B	B	A	A	A–	A–	C+
20	TWO-PIECE GLASS Opal Refl and Enam Bowl 	90° to 180°—12%  0° to 90°—53%	B	B	A	B+	B+	A–	B
21	ONE-PIECE GLASS Enameled Refl and Bowl 	90° to 180°—22%  0° to 90°—50%	B	B	A	B+	B	A–	A–
SEMI-INDIRECT AND INDIRECT LIGHTING UNITS									
22	LIGHT OPAL 	90° to 180°—60%  0° to 90°—25%	B–	C+	A	B+	B+	A–	C
23	DENSE OPAL (or Light Opal and Bowl-Enameled Lamp)	90° to 180°—70%  0° to 90°—10%	C+	C	A	A+	A	A+	C
24	ENAMELED METAL REFLECTOR Opal Glass Bottom 	90° to 180°—69%  0° to 90°—6[illegible]	C+	C	A	A+	A	A+	C
25	PRISMATIC ENCLOSED 	90° to 180°—57%  0° to 90°—26%	B–	C+	A	A–	A–	A–	B
26	CLEAR TOP ENCLOSED Enameled Glass 	90° to 180°—54%  0° to 90°—21%	C+	C	A	A+	A	A	B
27	MIRRORED INDIRECT 	90° to 180°—80%  0° to 90°—0%	C+	C	B+*	A+	A	A+	C
28	ENAMELED METAL INDIRECT 	90° to 180°—74%  0° to 90°—0%	C	C	B+	A+	A	A+	C

hand, in interpreting and enforcing the glare rule the inspector is not expected to insist upon what he may believe to be desirable practice in the given case; his duty is only to insure the absence of a condition which is prejudicial either to the health or to the safety of the worker.

" If a simple instrument were available for measuring glare the task of the inspector would be comparatively easy. However, there are so many factors entering into the situation that it has not been found practicable to develop any instrument which will properly evaluate them all. To arrive at an intelligent judgment in any given case, therefore, the inspector must be reasonably familiar with the principal factors in or causes of glare.

" **Causes of Glare.** — There are five principal causes of glare:

" 1. *Brightness of Source* — The light source may be too bright; that is, it may have too many candles per square inch of area.

" A glance at the sun proves that an extremely bright light source within the field of vision is capable of producing acute discomfort. Light sources of far lower brightness than the sun, such, for example, as the filament of an incandescent electric lamp or the incandescent mantle of a gas lamp, may also cause discomfort, although the annoying effect is usually not quite so marked.

" 2. *Total Volume of Light* — The light source may be too powerful for comfort; that is, it may give off too great a total candlepower in the direction of the eye.

" Too frequently glare is assumed to be entirely a question of the brightness of the light source; of equal importance is the question of its total candlepower. Experience has shown that a 500-watt lamp in a 10-inch opal globe, or a mercury-vapor lamp of an equivalent light output, hung 7 or 8 feet above the floor and a similar distance ahead of the observer, will prove quite as glaring as the exposed filament of a 50-watt incandescent lamp in the same location. The brightness of the opal-globe unit is only a few times that of a candle flame, but its total candlepower, and consequently the quantity of light which reaches the eye, is altogether too great, so that its effect is worse than that of the bare filament of lower candlepower, although the latter may have a brightness as high as 3000 candles per square inch. An unshaded window often causes glare, due, of course, to the large volume of light rather than to the high brightness of the sky.

" 3. *Location in the Field of View* — A given light source may be located at too short a distance from the eye, or it may lie too near the center of the field of vision, for comfort; that is, within too small an angle from the ordinary line of sight.

" The 500-watt opal-globe unit discussed in the previous illustration

would seldom cause discomfort if placed, say, 80 feet away from the observer, for at this distance the total quantity of light entering the eye would be only one one-hundredth of that received at 8 feet. Again, the same light source would probably be found quite unobjectionable at a distance of 8 feet from the eye provided this distance was obtained by locating the lamp 4 feet ahead of the observer and 7 feet above the eye level; in this case the lamp would scarcely be within the ordinary field of view.

"The natural position of the eye during intervals of rest from any kind of work is generally in the horizontal direction, and it is desirable that during such periods the worker should be freed from the annoyance caused by glare. Glare is the more objectionable the more nearly the light source approaches the direct line of sight. While at work the eye is usually directed either horizontally or at an angle below the horizontal. Glaring objects at or below the horizontal should especially be prohibited. The best way to remove light sources out of the direct line of vision is to locate them well up toward the ceiling. Local lamps, that is, lamps placed close to the work, if used at all, must be particularly well screened.

"4. *Contrast with Background* — The contrast may be too great between the light source and its darker surroundings.

"It is a common experience that a lamp viewed against a dark wall is far more trying to the eyes than when its surroundings appear relatively light. A light background requires, first: that the surface should be painted in a color which will reflect a considerable portion of the light which strikes it, and second: that the system of illumination employed should be such as to direct some light upon the background. In many cases the ceiling appears almost black under artificial light simply because no light reaches it. With daylight, on the other hand, the walls of a room are often so well illuminated that they appear brighter than the work itself and this, also, is a condition which is not conducive to good vision. In general, a light tone for ceilings and high side walls and a paint of medium reflecting power for the lower side walls will ordinarily be found most satisfactory under both artificial and natural lighting.

"Where strictly local lighting systems are employed, that is, where individual lamps are supplied for all benches and machines, and no overhead lighting is added, the resulting contrasts in illumination will usually be found so harsh as to be objectionable even though the lamps themselves are well shielded. The eyes of the workman, looking up from his brightly lighted machine or bench, are not adapted for vision at low illuminations; hence, if adjacent objects and aisles are only

dimly lighted, he will be compelled either to grope about, losing time and risking accident, or to wait until his eyes have become adapted to the low illumination. Glancing back at his work, he again loses time while his eyes adjust themselves to the increased amount of light which reaches them. If long continued, this condition leads to fatigue, as well as to interference with vision, and to accidents. In other words, where local lamps are employed, there should also be a system of overhead lighting which will provide a sufficient illumination of all surrounding areas to avoid such undesirable contrasts.

"5. *Time of Exposure* — The time of exposure may be too great, that is, the eye may be subjected to the strain caused by a light source of given strength within the field of vision for too long a time.

"Where an operator is seated and his field of vision is fixed for several hours at a time, light sources of lower brightness and lower candlepower are required than where the operator stands at his work and shifts his position and direction of view from time to time. In the first case the image of the light source is focused on one part of the retina for considerable periods of time and is obviously more likely to cause discomfort and eye-strain than when present for short periods only. Those who are forced to work all day at desks facing the windows are particularly likely to suffer from this form of glare.

"**Rating Light Sources from the Glare Standpoint.** — It is evident that the first two factors mentioned as causes of glare, namely, excessive brightness and excessive candlepower, concern the light source itself, whereas the third factor concerns its location in the field of view, and the fourth and fifth depend upon the conditions of its use.

"In Table XXXIV a means of rating light sources (into Grades I to X) has been provided which takes into account both their brightness and their candlepower. Light sources in Grades I and II may be termed soft or well diffused; those in Grades VIII, IX and X are harsh and likely to cause glare. It is seen from Table XXXIV that a light source of high intrinsic brightness but of low candlepower, — for example, one that would be classified under the fifth line of the first column (less than 20 cp. — and 100 to 1000 c. per sq. in.) has the same rating, Grade V, as a source of lower brightness but of greater total candlepower (2–5 c. per sq. in. and 500 total cp.) which falls in the second line of the fifth column.

"In accordance with the plan of Table XXXIV, measurements of brightness and candlepower have been made on a number of light sources found in everyday practice, both natural and artificial, and grades have been assigned to them as shown in Table XXXV. While engaged in his work, the inspector will, of course find other light sources in use which

are not included in the table; however, from those which are given he should be able to estimate closely in what grades the others should be placed. In cases of doubt, it is, of course, possible to have actual measurements made to determine both the brightness of the lighting unit and its total candlepower. The unit can then be rated in accordance with Table XXXIV.

TABLE XXXIV

CLASSIFICATION OF LIGHT SOURCES FROM THE STANDPOINT OF GLARE

Grade I indicates sources of maximum softness.
Grade X indicates sources of maximum harshness

Maximum Visible Brightness	Total Candlepower in Direction of Eye				
(Apparent Candles per Sq. In.)	Less than 20	20 to 50	50 to 150	150 to 500	500 to 2000
	Grade	Grade	Grade	Grade	Grade
Less than 2	I	I	II	II	III
2 to 5	II	II	III	IV	V
5 to 20	II	III	IV	VI	VII
20 to 100	IV	V	VI	VII	VIII
100 to 1000	V	VI	VII	VIII	IX
1000 and up	VI	VII	VIII	IX	X

TABLE XXXV

Specific Classification of Light Sources from the Standpoint of Glare as Derived from Table XXXIV

Natural Light Sources
(As seen through windows or skylights)

	Grade
Sun	X
Very Bright Sky	V
Dull Sky	III
Sun Showing on Prism Glass	IX

OPEN GAS FLAMES	II

INCANDESCENT MANTLE GAS LAMPS

	Mantles Consuming 2–5 Cu. Ft. per Hr.	Mantles Consuming 5–8 Cu. Ft. per Hr.	Large Single Mantle or Cluster 8–12 Cu. Ft. per Hr.	Large Single Mantle or Cluster 12–20 Cu. Ft. per Hr.	Cluster or High Pressure Lamp Consuming above 20 Cu. Ft. per Hr.
Clear Glassware	Grade V	Grade VI	Grade VII	Grade VIII	Grade IX
Frosted Globes	III	IV			
6-in. Opal Globe* 8-in. Opal Globe* 10-in. Opal Globe* 12-in. Opal Globe*	II I	III II	IV–VI III–V	V–VII	VI–VIII
Dome Reflector Mantle Visible Mantle not Visible	 V I	 VI II	 VII III	 VIII IV	 IX IV
Bowl Reflector Mantle Visible Mantle not Visible	 V II	 VI II	 VII III	 VIII V	 IX V
Totally Indirect* Semi-indirect Bowls*			I–II II–III	II II–IV	III III–VI

* Where a range is given, the best grade, that is the lowest, applies to globes that are evenly luminous, and the poorest to globes that have a decidedly bright spot in the center.

TABLE XXXV. — *Concluded*

ARC LAMPS

	Grade
Enclosed arcs, clear globes	IX
Flame arc, clear globes	X
Flame arc, opal globes	VII–VIII

MERCURY VAPOR TUBES	VI

CARBON AND METALLIZED FILAMENT INCANDESCENT LAMPS

8 cp.	V
16 cp.	V
32 cp.	VI

TUNGSTEN FILAMENT INCANDESCENT LAMPS

Watts	10–25	40–60	75–100	150–200	300	500–1000
Bare Lamps	Grade VI	Grade VII	Grade VIII	Grade IX	Grade IX	Grade X
Frosted Lamps or Frosted Globes	II	III	VI	VII	VIII	
8-in. Opal Globes*	I	I–II	II–IV	IV–VI		
12-in. Opal Globes*			II–III	II–V	IV–VI	VII–VIII
16-in. Opal Globes*				II–V	IV–VI	V–VII
Flat Reflectors — Filament Visible	VI	VII	VIII	IX	IX	X
Dome Reflectors — Steel or Dense Glass						
Filament visible from working position	VI	VII	VIII	IX	IX	X
Filament not visible from working position	I	I	III	III	IV	VI
Bowl Reflectors — Steel or Dense Glass						
Filament visible from working position	VI	VII	VIII	IX	IX	X
Filament not visible from working position	II	II	III	IV	VI	VII
Dome Reflectors — Bowl-enameled Lamps			IV	V	VI	VI
Semi-enclosing Units*			III–IV	IV–VI	IV–VII	VI–VIII
Totally Indirect Lighting*			I–II	I–II	II	III
Semi-indirect Bowl*			I–III	II–III	II–IV	III–VI

* Where a range is given, the best grade, that is the lowest, applies to globes that are evenly luminous, and the poorest to globes that have a decidedly bright spot in the center.

"From a study of Table XXXV, it will be observed that incandescent lamps equipped with reflectors which do not completely hide the light source have been assigned to the same grade as the corresponding sizes of bare lamps. It is true that the addition of a reflector somewhat increases the total candlepower in the direction of the eye and therefore the argument might be advanced that a 100-watt lamp with a flat reflector should be classified in Grade IX whereas the bare lamp is Grade VIII. On the other hand, from the standpoint of glare, the effect of the light background furnished by the reflector at least compensates for the increased candlepower which it gives; the rating is therefore kept at Grade VIII.

"**Charting the Field of View.** — It has already been pointed out that the distance between a light source and the eye, and its angle to the line of vision have much to do with determining how bright a light source may be used without discomfort." In Table XXXVI are given the ratings of the brightest light sources which are recommended for use in any given location in interior lighting. See also Fig. 110.

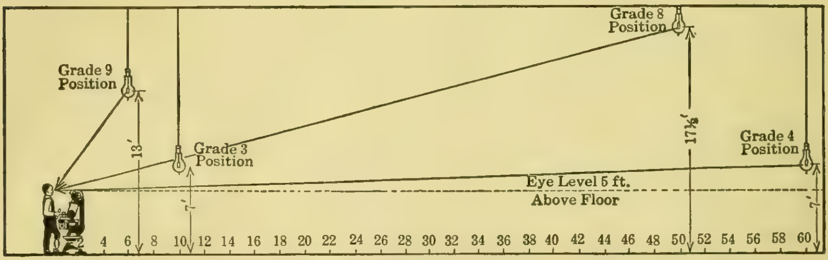


FIG. 110. How the Values of Table XXXVI Apply in a Factory Workroom.

"From Table XXXV the majority of *bare* incandescent lamps are seen to have a relatively poor rating; that is, most of them fall in Grades VII to IX, and it is evident from Table XXXVI that grades VII to IX are never to be recommended in work rooms in positions near the line of vision.

"It will be noted from Table XXXV that the sources of natural light, side and ceiling windows, usually fall in Grade IV. Grade II is the limiting value for light sources less than 6.5 feet high, in offices and other locations where the workers are seated facing in one direction for considerable periods of time. Hence, in these cases, to comply with the table, the work must be so arranged that the employees are not required to face windows where the sky is visible through the lower sash; that is, less than 6.5 feet above the floor.

"Prism glass, when so located as to catch the sun's rays, ordinarily

TABLE XXXVI

GRADES OF LIGHT SOURCES CONSIDERED GOOD PRACTICE IN ORDINARY MANUFACTURING OPERATIONS

For the present the limits set in this table cannot be rigidly applied to portable lamps used for temporary work such as setting up machines, repairing automobiles, etc.

Height above Floor in Feet	Horizontal Distance of Light Source From Observer in Feet															
	1	2	3	4	6	8	10	12	16	20	25	30	35	40	50	60 and Up
19 and Higher	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
18–19	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	8
17–18	9	9	9	9	9	9	9	9	9	9	9	9	8	8	8	8
16–17	9	9	9	9	9	9	9	9	9	9	8	8	8	8	6	6
15–16	9	9	9	9	9	9	9	9	9	8	8	8	8	6	6	6
14–15	9	9	9	9	9	9	9	9	9	8	8	8	8	6	6	6
13–14	9	9	9	9	9	9	9	9	8	8	8	8	6	6	6	6
12–13	9	9	9	9	9	9	8	8	8	8	6	6	6	6	6	6
11–12	9	9	9	9	9	8	8	8	8	8	6	6	5	5	5	5
10–11	9	9	9	9	9	8	8	8	6	6	5	5	5	5	5	5
9–10	9	9	9	9	8	8	6	6	6	5	5	5	5	5	5	5
8–9	9	9	9	8	8	6	5	5	4	4	4	4	4	4	4	5
7–8	9	9	8	6	5	5	4	4	4	4	4	4	4	4	4	4
6.5–7	9	6	5	4	4	3	3	3	3	3	3	3	3	3	3	4
6.5 or less	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3

BACKGROUND

Where the background and the surroundings are very dark in tone, a light source of one grade softer than that specified in this Table may be required. Where the background and surroundings are very light in tone one grade more harsh than that specified in the table may sometimes be permitted.

has a very much poorer rating than clear glass; hence, where it is used the installation of window shades or curtains should ordinarily be required.

"The question naturally arises why, if glare is so objectionable, all sources capable of producing glare should not be prohibited everywhere. The answer is that to attain a maximum softness of light sometimes entails a sacrifice in efficiency and an increase in operating expense. If a worker chooses unnecessarily to gaze directly upward at a bright skylight or at an artificial lighting unit so located that it is not a factor in glare under ordinary circumstances, it is scarcely within the province of a code of lighting to protect him from the consequences."

Specular Reflection. — A form of glare which is often less obvious than that which comes directly from the source to the eye, but which is

frequently more harmful because of its insidious nature, is that which comes to the eye as a glint or a reflection of the source in some polished surface. This form of glare, known as specular reflection or veiling glare, is frequently encountered where the work is with glossy paper, polished metal or furniture, or other shiny surfaces. It is particularly harmful because of the fact that the eye is often held to such surfaces for long periods of time, and while the glare may not be sufficiently annoying to be recognized as of a serious nature, it may, nevertheless, in time produce eye-fatigue or even permanent injury. Since the brightness of the reflected image is dependent upon the brightness of the light source, it follows that the harmful effects of specular reflection can be minimized by reducing the brightness of the light source. Frequently, specular reflections can be prevented from striking the eye by locating the light source in such a position with respect to the work that specularly reflected light will be thrown away from, rather than toward, the operator. The use of lighting units of large area and a diffusing medium to prevent any direct rays from the lamp striking the surfaces illuminated will aid in avoiding bad specular reflection; but on the other hand, if the source is very large, as, for example, a ceiling lighted by indirect units, a certain amount of specular reflection cannot be avoided. For a machine shop a more highly diffusing light source will be required than for a woodworking shop because the reflected images from metal are much more distinct than those from wood.

In choosing lighting equipment, it must be borne in mind that, although a given reflector may afford adequate protection against direct glare from the lamp filament, it will not protect against glaring reflections unless the lamp is shielded in such a manner that the filament cannot be seen when the unit is viewed from directly beneath. In many industrial operations, including the inspection of finished surfaces, a moderate degree of specular reflection or sheen will be found essential.

Desirable Wall Brightness. — The effectiveness of a lighting system depends, as has been shown, not only on the effectiveness of the lighting unit, but on the reflecting properties of the walls, ceiling and surroundings, and upon the size and proportions of the room. It is, in fact, entirely possible to find an installation of reflectors of poor design and inferior from the standpoint of glare, which is, nevertheless, from the single standpoint of the percentage of light reaching the illumination plane, better than an installation where reflectors of good design are used, if the former are installed under favorable conditions such as light walls, ceilings, etc., and the latter under unfavorable conditions. On the other hand, it must be borne in mind that a large expanse of wall surface, finished so light as to reflect a large volume of light into the eye,

is objectionable for offices, residences and all rooms where the occupants are likely to sit more or less directly facing the walls for considerable periods of time. Such data as are available indicate that where the brightness of the walls is equal to, or greater than the brightness of white paper lying on the table or desk, annoying glare will result. In fact, a wall brightness one-half that of the paper has been found unsatisfactory and a brightness of 20 per cent is apparently comfortable. With the usual types of lighting units, walls are not illuminated to intensities as high as those obtaining on desk or table tops, and walls which reflect less than 50 per cent of the light which strikes them should not produce discomfort, provided, of course, that they are of a matte or semi-matte finish. Walls finished in buff, light green or gray reflect about the proper proportion of light and their use is meeting with general favor. Walls finished in a high gloss are not satisfactory from a glare standpoint.

Shadow. — Shadows may be troublesome if they are sharp or so dark that it becomes difficult to distinguish between shadows and objects, or if the illumination in the shadows is insufficient for good vision. With general lighting, shadows from the work or fixed objects can be reduced by placing the units high and close together. A maximum degree of shadow results from this arrangement in the case of direct lighting systems using clear lamps in open reflectors of small area, a minimum in that of totally indirect lighting systems. Enclosing and semi-enclosing units produce shadows which are softer than those produced by open reflectors but much heavier than those produced by totally indirect systems. With semi-indirect units, almost any degree of shadow can be obtained by varying the density of the glass.

In observing objects in their three dimensions, shadows are an aid to vision in that the surfaces can be more easily distinguished from one another than if they were all lighted to the same intensity. However, while shadows are of great value in the discernment of irregularities of surfaces, they are of little or no value in the observation of plain surfaces. For example, while shadows are highly desirable in industrial work, in office work they are for the most part unnecessary, and, in fact, often a nuisance. With few exceptions, only soft, luminous shadows are desirable in interior lighting; those having sharp edges are objectionable.

Coefficients of Utilization. — Because of the loss of light through absorption by the reflector or enclosing glassware, by the fixture, and by the walls and ceiling, only a part of the total light emitted by a lamp reaches the designated plane. Of the warp of the light sent in directions other than those where it is used, some will be redirected by the ceiling,

walls and other surfaces on which it falls, and the percentage of the total lumens emitted by the lamp which ultimately reaches the desired location will, therefore, vary widely with the proportions of the room and the nature of the surroundings. Contrary to the general belief, the absolute height in feet at which units are mounted has in itself no influence upon the percentage of light utilized, so long as the same proportions are maintained. For example, if there are two buildings, one 20 feet by 50 feet and 10 feet in height, and the other 40 feet by 100 feet and 20 feet in height, it is clear from Fig. 111 that the effective angle

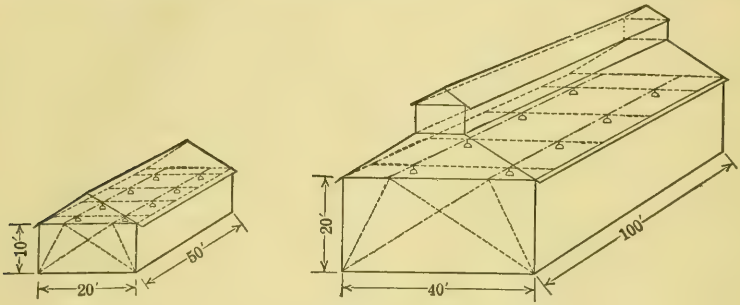


FIG. 111. Illustration of Effective Angle.

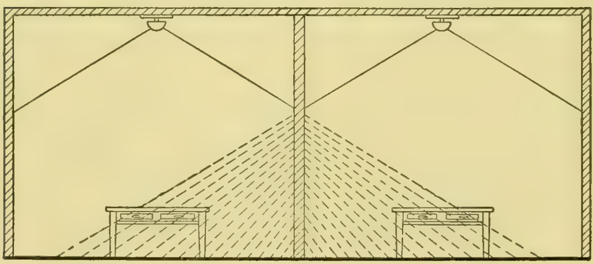


FIG. 112. The Coefficient of Utilization is Dependent upon Room Proportions. The Light Striking the Partition is Largely Lost.

and hence the efficiencies of the lighting systems in the two buildings will be the same. If the small building is illuminated by eight 100-watt lamps on 10-foot centers and the large building by the same number of 400-watt lamps on 20-foot centers, the average intensity of illumination will be the same, and its distribution will be similar. On the other hand, the *proportions* of a given building or room have a very important bearing upon the percentage of light utilized. For rooms in which the ratio of width to ceiling height is small, a low utilization obtains because, as shown in Fig. 112, a relatively greater portion of the light strikes the walls and is absorbed by them than is the case for a large room.

Room Index. — Again, it is obvious that a square room would have a higher coefficient of utilization than a long narrow room of the same area. As the result of an elaborate series of tests made in rooms of different dimensions, it has been found possible to classify all lighting installations in ordinary rooms into groups depending upon the length and width of the room, and the height of the light sources above the plane to be illuminated. These classifications are given in Table XXXVII and are known as room indices. These indices are chosen arbitrarily. For direct lighting systems in square rooms, the room index equals

$$\frac{\text{width of room}}{2 \times \text{height from plane of work to lamps}}.$$

For indirect and semi-indirect installations, the room index equals

$$\frac{\text{width of room}}{1\frac{1}{3} \times \text{height from plane of work to ceiling}}.$$

For an installation in a cubical room, the index will be 1 when the distance between the lighting fixtures and the plane of work is $\frac{1}{2}$ of the total distance from floor to ceiling.

Room indices for other than square rooms can only be compiled from test data. For example, the coefficient of utilization and the room index for a rectangular room is not the same as for a square room of equivalent area but must be determined empirically.

Table XXXVIII shows the coefficients of utilization for various types of lighting units in rooms having walls and ceilings of different reflecting power and for each room index. These coefficients of utilization are based on actual test results. It is obvious that for any given location the coefficients of utilization for two different types of lighting units represent the relative efficiency in delivering light upon a horizontal plane under those particular conditions.

TABLE XXXVII

Room Index

Classify the room according to the proportions and the mounting height above the plane of work. Use upper column headings for direct-lighting units; for semi-indirect and totally indirect units choose column at bottom of page. Wherever the circumstances are such that the room index falls between two given figures, use the smaller number.

Room Width	Room Length	Direct Lighting Units — Height Above Plane of Work — Feet											
Feet	Feet	4	5	6	7	8	9	10	12	14	16	20	24
8	10	1.0	0.8	0.8	0.6	0.6	0.6	0.6	...	...	...	...	...
	12	1.25	0.8	0.8	0.6	0.6	0.6	0.6	...	...	...	...	...
	16	1.25	1.0	0.8	0.6	0.6	0.6	0.6	...	...	...	...	...
	24	1.5	1.25	1.0	0.8	0.6	0.6	0.6	0.6	0.6	...	...	...
	35	1.5	1.25	1.25	1.0	0.8	0.8	0.6	0.6	0.6	0.6	...	...
	50	2.0	1.5	1.25	1.0	1.0	0.8	0.8	0.6	0.6	0.6	...	...
10	10	1.25	1.0	0.8	0.6	0.6	0.6	0.6	...	...	...	...	...
	14	1.5	1.0	1.0	0.8	0.6	0.6	0.6	0.6	...	...	...	...
	20	1.5	1.25	1.0	0.8	0.8	0.6	0.6	0.6	0.6	...	...	...
	30	2.0	1.5	1.25	1.0	0.8	0.8	0.6	0.6	0.6	0.6	...	...
	40	2.0	1.5	1.5	1.25	1.0	1.0	0.8	0.6	0.6	0.6	0.6	...
	70	2.0	1.5	1.5	1.25	1.25	1.0	1.0	0.8	0.8	0.6	0.6	...
12	12	1.5	1.25	1.0	0.8	0.8	0.6	0.6	0.6	...	...	...	...
	18	1.5	1.25	1.25	1.0	0.8	0.8	0.6	0.6	0.6	...	...	...
	24	2.0	1.5	1.25	1.0	1.0	0.8	0.8	0.6	0.6	0.6	...	...
	35	2.0	1.5	1.5	1.25	1.0	1.0	0.8	0.6	0.6	0.6	0.6	...
	50	2.0	2.0	1.5	1.5	1.25	1.0	1.0	0.8	0.6	0.6	0.6	0.6
	90	2.0	2.0	1.5	1.5	1.25	1.25	1.25	1.0	0.8	0.8	0.6	0.6
14	14	1.5	1.5	1.25	1.0	0.8	0.8	0.6	0.6	0.6	...	...	...
	24	2.0	1.5	1.5	1.25	1.0	1.0	0.8	0.6	0.6	0.6	...	...
	40	2.5	2.0	1.5	1.5	1.25	1.0	1.0	0.8	0.6	0.6	0.6	0.6
	70	2.5	2.0	2.0	1.5	1.5	1.25	1.25	1.0	0.8	0.8	0.6	0.6
	100	2.5	2.0	2.0	1.5	1.5	1.5	1.5	1.25	0.8	0.8	0.6	0.6
16	16	2.0	1.5	1.25	1.25	1.0	0.8	0.8	0.6	0.6	0.6	...	...
	30	2.5	2.0	1.5	1.5	1.25	1.0	1.0	0.8	0.6	0.6	0.6	...
	50	2.5	2.0	2.0	1.5	1.5	1.25	1.25	1.0	0.8	0.6	0.6	0.6
	80	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.25	1.0	0.8	0.6	0.6
	120	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.0	1.0	0.8	0.8
18	18	2.0	2.0	1.5	1.25	1.0	1.0	0.8	0.8	0.6	0.6	...	...
	35	3.0	2.5	2.0	1.5	1.5	1.25	1.0	1.0	0.8	0.6	0.6	0.6
	50	3.0	2.5	2.0	2.0	1.5	1.5	1.25	1.0	0.8	0.8	0.6	0.6
	80	3.0	2.5	2.0	2.0	2.0	1.5	1.5	1.25	1.0	0.8	0.8	0.6
	120	3.0	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.25	1.0	0.8	0.8
20	20	2.5	2.0	1.5	1.5	1.25	1.0	1.0	0.8	0.6	0.6	0.6	...
	40	3.0	2.5	2.0	2.0	1.5	1.5	1.25	1.0	0.8	0.8	0.6	0.6
	60	3.0	2.5	2.5	2.0	2.0	1.5	1.5	1.25	1.0	0.8	0.6	0.6
	100	3.0	2.5	2.5	2.0	2.0	2.0	1.5	1.5	1.25	1.0	0.8	0.6
	140	3.0	2.5	2.5	2.0	2.0	2.0	1.5	1.5	1.25	1.25	1.0	0.8

TABLE XXXVII

ROOM INDEX. — *Continued*

Room Width	Room Length	DIRECT LIGHTING UNITS —Height Above Plane of Work —Feet—											
Feet	Feet	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**14**	**16**	**20**	**24**
24	24	3.0	2.5	2.0	1.5	1.5	1.25	1.25	1.0	0.8	0.8	0.6	0.6
	50	3.0	3.0	2.5	2.0	2.0	1.5	1.5	1.25	1.0	1.0	0.8	0.6
	70	3.0	3.0	2.5	2.5	2.0	2.0	1.5	1.5	1.25	1.0	0.8	0.6
	100	3.0	3.0	2.5	2.5	2.0	2.0	2.0	1.5	1.5	1.25	1.0	0.8
	160	3.0	3.0	2.5	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.25	1.0
30	30	4.0	3.0	2.5	2.0	2.0	1.5	1.5	1.25	1.0	1.0	0.8	0.6
	60	4.0	3.0	3.0	2.5	2.5	2.0	2.0	1.5	1.25	1.25	1.0	0.8
	100	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	1.5	1.5	1.0	0.8
	140	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0	1.5	1.25	1.0
35	35	4.0	3.0	3.0	2.5	2.0	2.0	1.5	1.5	1.25	1.0	0.8	0.6
	70	5.0	4.0	3.0	3.0	3.0	2.5	2.0	2.0	1.5	1.5	1.0	0.8
	100	5.0	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	1.5	1.25	1.0
	140	5.0	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	1.5	1.5	1.25
40	40	5.0	4.0	3.0	3.0	2.5	2.0	2.0	1.5	1.5	1.25	1.0	0.8
	80	5.0	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	1.5	1.25	1.0
	140	5.0	4.0	3.0	3.0	3.0	2.5	2.5	2.5	2.0	2.0	1.5	1.25
50	50	5.0	5.0	4.0	4.0	3.0	2.5	2.5	2.0	2.0	1.5	1.25	1.0
	100	5.0	5.0	4.0	4.0	3.0	3.0	3.0	2.5	2.5	2.0	1.5	1.25
	200	5.0	5.0	4.0	4.0	3.0	3.0	3.0	2.5	2.5	2.5	2.0	1.5
60	60	5.0	5.0	5.0	4.0	4.0	3.0	3.0	2.5	2.0	2.0	1.5	1.25
	100	5.0	5.0	5.0	5.0	4.0	4.0	3.0	3.0	2.5	2.0	1.5	1.5
	200	5.0	5.0	5.0	5.0	4.0	4.0	3.0	3.0	3.0	2.5	2.0	2.0
70	70	5.0	5.0	5.0	5.0	4.0	4.0	3.0	3.0	2.5	2.0	1.5	1.5
	140	5.0	5.0	5.0	5.0	5.0	4.0	4.0	3.0	3.0	3.0	2.0	2.0
	200	5.0	5.0	5.0	5.0	5.0	4.0	4.0	3.0	3.0	3.0	2.5	2.0
80	80	5.0	5.0	5.0	5.0	5.0	4.0	4.0	4.0	3.0	2.5	2.0	1.5
	140	5.0	5.0	5.0	5.0	5.0	5.0	4.0	4.0	3.0	3.0	3.0	2.5
100	100	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.0	4.0	3.0	2.5	2.0
	200	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.0	4.0	3.0	3.0	2.5
		6	**7½**	**9**	**10½**	**12**	**13½**	**15**	**18**	**21**	**24**	**30**	**36**
		SEMI AND INDIRECT LIGHTING UNITS — Ceiling Height Above Plane of Work.											

TABLE XXXVIII

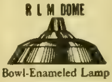
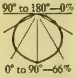
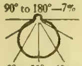
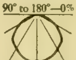
	COLOR REFLECTION FACTOR — CEILING		VERY LIGHT (70%)			FAIRLY LIGHT (50%)			FAIRLY DARK (30%)	
	COLOR REFLECTION FACTOR — WALLS		FAIRLY LIGHT (50%)	FAIRLY DARK (30%)	VERY DARK (10%)	FAIRLY LIGHT (50%)	FAIRLY DARK (30%)	VERY DARK (10%)	FAIRLY DARK (30%)	VERY DARK (10%)
	REFLECTOR TYPE	ROOM INDEX	COEFFICIENTS OF UTILIZATION							
1	R L M DOME	0.6	.34	.29	.24	.34	.29	.24	.28	.24
		0.8	.42	.38	.34	.42	.37	.33	.37	.33
		1.0	.46	.43	.39	.45	.42	.39	.42	.39
		1.25	.50	.47	.43	.49	.46	.43	.45	.42
	Clear Lamp	1.5	.53	.50	.46	.52	.49	.46	.48	.45
	90° to 180°—0%	2.0	.58	.55	.51	.57	.54	.51	.53	.51
		2.5	.62	.59	.56	.61	.58	.56	.58	.56
		3.0	.64	.61	.58	.63	.60	.58	.60	.58
		4.0	.67	.65	.63	.66	.64	.62	.63	.61
	0° to 90°—76%	5.0	.69	.67	.65	.67	.66	.64	.65	.63
2	R L M DOME	0.6	.32	.28	.25	.32	.28	.25	.27	.25
		0.8	.40	.36	.34	.39	.35	.33	.35	.33
		1.0	.43	.39	.37	.42	.39	.37	.39	.37
		1.25	.46	.43	.41	.45	.43	.41	.43	.41
	Bowl-Enameled Lamp	1.5	.48	.45	.43	.47	.45	.43	.45	.43
	90° to 180°—0%	2.0	.52	.50	.48	.51	.49	.47	.49	.47
		2.5	.56	.54	.52	.55	.53	.51	.53	.51
		3.0	.57	.55	.53	.56	.54	.52	.54	.52
		4.0	.60	.58	.56	.59	.57	.55	.57	.55
	0° to 90°—66%	5.0	.61	.59	.57	.60	.58	.57	.58	.56
3	GLASSTEEL DIFFUSER	0.6	.29	.25	.21	.28	.24	.21	.23	.21
		0.8	.36	.32	.29	.35	.31	.28	.31	.28
		1.0	.39	.36	.33	.38	.35	.33	.34	.32
		1.25	.42	.39	.36	.41	.38	.36	.37	.35
		1.5	.45	.42	.39	.43	.40	.38	.39	.38
	90° to 180°—7%	2.0	.49	.46	.43	.48	.45	.43	.44	.42
		2.5	.53	.50	.47	.51	.49	.47	.47	.46
		3.0	.54	.52	.49	.52	.50	.49	.49	.47
		4.0	.57	.55	.53	.55	.53	.51	.51	.50
	0° to 90°—60%	5.0	.58	.56	.54	.56	.54	.53	.52	.51
4	DEEP BOWL	0.6	.31	.26	.23	.30	.26	.23	.25	.23
		0.8	.38	.34	.31	.37	.34	.31	.33	.31
		1.0	.41	.38	.35	.41	.38	.35	.37	.35
		1.25	.44	.41	.38	.44	.41	.38	.40	.38
	Clear Lamp	1.5	.47	.44	.41	.46	.43	.41	.43	.41
	90° to 180°—0%	2.0	.51	.48	.45	.50	.47	.45	.47	.45
		2.5	.54	.51	.49	.53	.51	.49	.51	.49
		3.0	.56	.54	.51	.55	.53	.51	.53	.51
		4.0	.58	.56	.54	.57	.55	.54	.55	.53
	0° to 90°—65%	5.0	.60	.58	.56	.58	.57	.55	.56	.55
5	DEEP BOWL	0.6	.29	.26	.23	.29	.26	.23	.25	.23
		0.8	.35	.33	.31	.35	.32	.30	.32	.30
		1.0	.38	.36	.34	.38	.36	.34	.35	.34
		1.25	.41	.39	.37	.41	.39	.37	.38	.37
	Bowl-Enameled Lamp	1.5	.44	.41	.39	.43	.41	.39	.40	.39
	90° to 180°—0%	2.0	.47	.45	.43	.46	.44	.43	.43	.43
		2.5	.50	.48	.46	.49	.47	.46	.46	.46
		3.0	.51	.49	.47	.50	.48	.47	.47	.47
		4.0	.53	.51	.50	.52	.50	.49	.49	.49
	0° to 90°—58%	5.0	.54	.52	.51	.53	.51	.50	.50	.49
6	FLAT CONE Shielding Band	0.6	.27	.23	.21	.26	.23	.21	.23	.21
		0.8	.32	.30	.28	.32	.29	.27	.29	.27
		1.0	.35	.33	.31	.35	.33	.31	.32	.31
		1.25	.38	.36	.34	.37	.36	.34	.35	.34
		1.5	.40	.38	.36	.39	.37	.36	.37	.36
	Clear Lamp 90° to 180°—1%	2.0	.43	41	.39	.42	.41	.39	.40	.39
		2.5	.46	.44	.42	.45	.43	.42	.43	.42
		3.0	.47	.45	.43	.46	.44	.43	.44	.43
		4.0	.49	.47	.46	.48	.46	.45	.46	.45
	0° to 90°—54%	5.0	.50	.48	.47	.49	.47	.46	.47	.46
7	FLAT CONE	0.6	.26	.20	.16	.26	.19	.16	.19	.16
		0.8	.32	.26	.22	.32	.26	.22	.26	.22
		1.0	.36	.30	.26	.36	.30	.26	.30	.26
		1.25	.41	.35	.30	.39	.34	.30	.33	.30
	Clear Lamp	1.5	44	.38	.33	.42	.37	.33	.36	.33
	90° to 180°—10%	2.0	.50	44	.38	.48	.43	.38	.42	.38
		2.5	.54	.48	.42	.52	.47	.42	.46	.42
		3.0	.57	.51	.46	.55	.50	.45	.49	.45
		4.0	.62	.56	.51	.60	.54	.50	.53	.50
	0° to 90°—74%	5.0	.65	.60	.54	.62	.56	.53	.55	.53

TABLE XXXVIII. — *Continued*

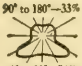
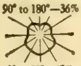
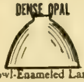
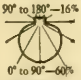
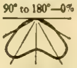
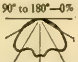
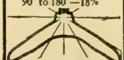
	Color Reflection Factor	Ceiling	Very Light (70%)			Fairly Light (50%)			Fairly Dark (30%)	
		Walls	Fairly Light (50%)	Fairly Dark (30%)	Very Dark (10%)	Fairly Light (50%)	Fairly Dark (30%)	Very Dark (10%)	Fairly Dark (30%)	Very Dark (10%)
	Reflector Type	Room Index	COEFFICIENTS OF UTILIZATION							
8	LIGHT DENSITY OPAL	0.6	.26	.21	.17	.24	.19	.16	.18	.15
		0.8	.32	.27	.23	.30	.25	.22	.24	.21
	Clear Lamp	1.0	.36	.31	.27	.34	.29	.26	.27	.24
		1.25	.40	.35	.31	.37	.32	.29	.30	.27
		1.5	.44	.38	.34	.40	.35	.32	.32	.30
	90° to 180°—33%	2.0	.49	.44	.39	.45	.40	.37	.37	.34
		2.5	.53	.48	.44	.49	.44	.41	.40	.38
		3.0	.56	.51	.47	.51	.46	.43	.42	.40
		4.0	.60	.55	.51	.55	.50	.47	.46	.44
	0° to 90°—54%	5.0	.62	.58	.54	.57	.53	.50	.48	.46
9	LIGHT DENSITY OPAL	0.6	.22	.17	.14	.20	.16	.13	.14	.12
		0.8	.27	.22	.19	.25	.21	.18	.19	.16
	Bowl-Enameled Lamp	1.0	.31	.26	.23	.28	.24	.21	.22	.19
		1.25	.35	.30	.26	.31	.27	.24	.24	.22
		1.5	.38	.33	.29	.34	.30	.26	.27	.24
	90° to 180°—36%	2.0	.43	.38	.34	.38	.34	.31	.30	.28
		2.5	.47	.42	.38	.42	.38	.34	.34	.31
		3.0	.49	.44	.40	.44	.40	.37	.36	.33
		4.0	.53	.49	.45	.48	.44	.41	.39	.37
	0° to 90°—45%	5.0	.56	.52	.48	.50	.46	.43	.40	.39
10	DENSE OPAL	0.6	.32	.27	.23	.31	.26	.22	.25	.22
		0.8	.40	.35	.31	.38	.34	.31	.33	.30
	Clear Lamp	1.0	.44	.39	.36	.42	.38	.35	.37	.35
		1.25	.47	.43	.40	.46	.42	.39	.40	.38
		1.5	.51	.47	.43	.49	.45	.42	.43	.41
	90° to 180°—15%	2.0	.56	.52	.48	.54	.50	.47	.48	.46
		2.5	.60	.56	.53	.57	.54	.52	.52	.50
		3.0	.63	.59	.55	.60	.56	.54	.54	.52
		4.0	.66	.63	.60	.63	.60	.58	.57	.55
	0° to 90°—67%	5.0	.67	.65	.62	.65	.61	.59	.59	.57
11	DENSE OPAL	0.6	.29	.24	.20	.28	.23	.20	.22	.20
		0.8	.35	.31	.28	.34	.30	.27	.29	.27
	Bowl-Enameled Lamp	1.0	.39	.35	.32	.38	.34	.32	.33	.31
		1.25	.43	.39	.36	.41	.38	.35	.36	.34
		1.5	.46	.42	.38	.44	.40	.37	.38	.36
	90° to 180°—16%	2.0	.51	.47	.44	.48	.45	.42	.43	.41
		2.5	.55	.51	.48	.52	.49	.46	.47	.45
		3.0	.57	.54	.50	.54	.51	.48	.48	.46
		4.0	.60	.57	.54	.57	.54	.52	.51	.50
	0° to 90°—60%	5.0	.62	.59	.56	.58	.56	.54	.53	.52
12	MIRRORED GLASS	0.6	.32	.27	.24	.31	.27	.24	.27	.24
		0.8	.39	.35	.32	.39	.35	.32	.35	.32
	Clear Lamp	1.0	.43	.39	.37	.42	.39	.37	.39	.37
		1.25	.46	.43	.40	.46	.43	.40	.42	.40
		1.5	.49	.46	.43	.48	.45	.43	.45	.43
	90° to 180°—0%	2.0	.53	.50	.48	.52	.50	.48	.49	.48
		2.5	.57	.54	.52	.56	.54	.52	.53	.52
		3.0	.58	.56	.54	.57	.55	.54	.54	.53
		4.0	.61	.59	.57	.60	.58	.56	.57	.56
	0° to 90°—68%	5.0	.63	.61	.58	.61	.59	.58	.58	.57
13	MIRRORED GLASS	0.6	.26	.22	.19	.25	.22	.19	.21	.19
		0.8	.32	.29	.26	.31	.28	.26	.28	.26
	Bowl-Enameled Lamp	1.0	.35	.32	.30	.34	.32	.30	.31	.30
		1.25	.38	.35	.33	.37	.35	.33	.34	.33
		1.5	.40	.37	.35	.39	.37	.35	.36	.35
	90° to 180°—0%	2.0	.43	.41	.39	.42	.40	.39	.40	.39
		2.5	.46	.44	.42	.45	.43	.42	.43	.42
		3.0	.47	.46	.44	.46	.45	.44	.44	.43
		4.0	.49	.48	.46	.48	.47	.46	.46	.45
	0° to 90°—55%	5.0	.50	.49	.47	.49	.48	.47	.47	.46
14	PRISMATIC INDUSTRIAL	0.6	.33	.26	.21	.31	.25	.21	.24	.20
		0.8	.41	.35	.30	.39	.33	.29	.32	.29
	Clear Lamp	1.0	.45	.40	.35	.43	.39	.34	.37	.33
		1.25	.50	.44	.39	.47	.42	.38	.40	.37
	90° to 180°—18%	1.5	.52	.48	.43	.50	.45	.42	.43	.40
		2.0	.58	.54	.49	.56	.51	.47	.49	.46
		2.5	.63	.59	.54	.60	.56	.53	.54	.51
		3.0	.66	.62	.58	.63	.59	.56	.56	.54
		4.0	.71	.67	.63	.67	.63	.61	.60	.58
	0° to 90°—73%	5.0	.73	.69	.66	.69	.65	.63	.62	.60

TABLE XXXVIII. — *Continued*

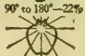
	Color Reflection Factor	Ceiling	Very Light (70%)			Fairly Light (50%)			Fairly Dark (30%)	
		Walls	Fairly Light (50%)	Fairly Dark (30%)	Very Dark (10%)	Fairly Light (50%)	Fairly Dark (30%)	Very Dark (10%)	Fairly Dark (30%)	Very Dark (10%)
	Reflector Type	Room Index	Coefficients of Utilization							
15	Diffusing Globe	0.6	.18	.13	.10	.16	.12	.10	.10	.09
	Light Opal	0.8	.22	.17	.14	.20	.16	.13	.14	.12
		1.0	.26	.21	.18	.23	.19	.16	.17	.14
		1.25	.29	.24	.21	.26	.22	.19	.19	.16
		1.5	.32	.27	.23	.29	.24	.21	.22	.19
	90° to 180°—35%	2.0	.37	.32	.28	.32	.28	.25	.25	.22
		2.5	.40	.35	.31	.35	.31	.28	.28	.25
		3.0	.43	.38	.34	.38	.33	.30	.30	.27
		4.0	.47	.42	.38	.41	.37	.34	.33	.31
	0° to 90°—40%	5.0	.49	.45	.41	.43	.39	.36	.34	.33
16	One-Piece Opal	0.6	.22	.17	.14	.20	.16	.13	.14	.12
	Flattened Reflecting Top	0.8	.27	.22	.19	.25	.21	.18	.19	.17
		1.0	.31	.26	.23	.28	.24	.21	.22	.19
		1.25	.35	.30	.26	.31	.27	.24	.25	.22
		1.5	.38	.33	.29	.34	.30	.27	.27	.24
	90° to 180°—35%	2.0	.42	.38	.33	.38	.34	.31	.31	.28
		2.5	.46	.41	.37	.41	.37	.34	.34	.31
		3.0	.49	.45	.40	.43	.39	.36	.36	.33
		4.0	.53	.48	.44	.47	.43	.40	.38	.36
	0° to 90°—45%	5.0	.55	.51	.47	.49	.45	.42	.40	.38
17	Prismatic Enclosing	0.6	.28	.22	.18	.26	.21	.17	.19	.16
		0.8	.35	.29	.25	.33	.28	.24	.26	.23
		1.0	.38	.33	.29	.36	.32	.28	.30	.27
		1.25	.43	.37	.33	.40	.35	.31	.33	.30
		1.5	.46	.41	.36	.43	.38	.34	.35	.33
	90° to 180°—27%	2.0	.51	.46	.42	.47	.43	.40	.40	.38
		2.5	.55	.51	.46	.51	.47	.44	.44	.42
		3.0	.58	.54	.50	.54	.50	.47	.46	.44
		4.0	.62	.58	.55	.57	.54	.51	.50	.48
	0° to 90°—59%	5.0	.65	.61	.57	.60	.56	.53	.52	50
18	Semi-Enclosing	0.6	.22	.17	.13	.21	.16	.13	.15	.13
	Metal Reflector	0.8	.28	.22	.19	.26	.21	.18	.21	.18
		1.0	.31	.26	.23	.30	.25	.22	.24	.21
		1.25	.35	.30	.26	.32	.28	.25	.27	.24
		1.5	.38	.33	.28	.36	.31	.27	.30	.26
	90° to 180°—20%	2.0	.43	.38	.33	.40	.36	.32	.34	.30
		2.5	.46	.41	.37	.44	.39	.36	.37	.34
		3.0	.49	.44	.40	.46	.42	.38	.40	.37
		4.0	.54	.49	.44	.50	.45	.42	.43	.40
	0° to 90°—56%	5.0	.56	.51	.47	.52	.47	.45	.44	.43
19	Semi-Enclosing	0.6	.24	.18	.14	.23	.18	.14	.17	.14
	Compo Reflector	0.8	.30	.24	.21	.29	.24	.20	.23	.20
		1.0	.33	.28	.25	.32	.28	.24	.27	.24
		1.25	.37	.32	.28	.35	.31	.27	.30	.27
		1.5	.39	.35	.31	.38	.34	.30	.32	.29
	90° to 180°—13%	2.0	.44	.40	.35	.42	.38	.34	.37	.34
		2.5	.48	.44	.39	.46	.42	.38	.41	.38
		3.0	.50	.46	.42	.48	.44	.41	.43	.40
		4.0	.55	.51	.47	.53	.49	.45	.46	.44
	0° to 90°—60%	5.0	.57	.53	.49	.54	.50	.47	.48	.46
20	Two-Piece Glass	0.6	.22	.17	.14	.21	.17	.14	.16	.14
	Opal Reflector and Enameled Bowl	0.8	.27	.23	.20	.26	.22	.19	.22	.19
		1.0	.30	.26	.23	.29	.26	.23	.25	.22
		1.25	.33	.29	.26	.32	.28	.26	.29	.25
		1.5	.36	.32	.29	.35	.31	.28	.31	.27
	90° to 180°—12%	2.0	.41	.37	.33	.39	.35	.32	.34	.31
		2.5	.44	.40	.36	.42	.38	.35	.37	.35
		3.0	.46	.42	.38	.43	.40	.37	.39	.37
		4.0	.49	.45	.42	.47	.43	.41	.42	.40
	0° to 90°—53%	5.0	.51	.48	.44	.48	.45	.43	.43	.41
21	One-Piece Glass	0.6	.22	.17	.14	.21	.16	.14	.15	.14
	Enameled Reflector and Bowl	0.8	.27	.23	.20	.26	.22	.19	.20	.18
		1.0	.30	.26	.23	.29	.25	.22	.23	.21
		1.25	.34	.30	.26	.32	.28	.25	.26	.24
		1.5	.37	.33	.29	.34	.30	.27	.28	.26
	90° to 180°—22%	2.0	.41	.37	.33	.38	.34	.31	.32	.30
		2.5	.44	.40	.36	.41	.38	.35	.35	.33
		3.0	.47	.43	.39	.43	.40	.37	.37	.35
		4.0	.51	.47	.43	.47	.44	.41	.41	.39
	0° to 90°—50%	5.0	.53	.49	.45	.48	.45	.42	.42	.40

TABLE XXXVIII. — *Concluded*

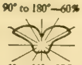
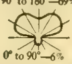
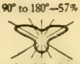
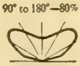
	COLOR REFLECTION FACTOR — CEILING		VERY LIGHT (70%)			FAIRLY LIGHT (50%)			FAIRLY DARK (30%)	
	COLOR REFLECTION FACTOR — WALLS		FAIRLY LIGHT (50%)	FAIRLY DARK (30%)	VERY DARK (10%)	FAIRLY LIGHT (50%)	FAIRLY DARK (30%)	VERY DARK (10%)	FAIRLY DARK (30%)	VERY DARK (10%)
	REFLECTOR TYPE	ROOM INDEX	COEFFICIENTS OF UTILIZATION							
22	LIGHT OPAL	0.6	.18	.14	.11	.15	.12	.09	.09	.07
		0.8	.22	.18	15	.19	.15	.12	.12	.10
		1.0	.26	.22	.18	.22	.18	.15	.14	.12
		1.25	.30	.25	.22	.25	.21	.18	.16	.14
		1.5	.33	.28	.24	.27	.23	.20	.18	.16
	90° to 180°—60%	2.0	.38	.33	.29	.31	.27	.24	.21	.19
		2.5	.41	.36	.32	.34	.30	.27	.24	.22
		3.0	.44	.39	.35	.36	.32	.29	.25	.23
		4.0	49	.44	.40	.40	.36	.33	.28	.26
	0° to 90°—25%	5.0	.51	.46	.42	.42	.38	.35	.29	.28
23	DENSE OPAL (or Light Opal and Bowl-enameled Lamp)	0.6	.16	.13	.11	.12	.10	.08	.07	.06
		0.8	.20	.17	.15	.16	.13	.11	.09	.08
		1.0	.23	.20	.17	.18	.15	.13	.10	.09
		1.25	.27	.23	.20	.21	.18	.16	.12	.11
		1.5	.29	.26	.22	.23	.19	.17	.13	.12
	90° to 180°—70%	2.0	.33	.29	.26	.26	.22	.20	.15	.14
		2.5	.36	.32	.29	.28	.25	.23	.17	.16
		3.0	.39	.35	.32	.29	.27	.25	.18	.17
		4.0	.43	.39	.36	.32	.30	.28	.20	.19
	0° to 90°—10%	5.0	.45	.41	.38	.34	.32	.30	.22	.20
24	ENAMELED METAL REFLECTOR Opal Glass Bottom	0.6	.16	.13	.11	.12	.10	.08	.07	.06
		0.8	.19	.16	.14	.15	.13	.11	.08	.08
		1.0	.22	.19	.17	.17	.15	.13	.10	.09
		1.25	.25	.22	.19	.20	.17	.15	.11	.10
		1.5	.27	.24	.21	.21	.18	.16	.12	.11
	90° to 180°—69%	2.0	.31	.28	.25	.24	.21	.19	.14	.13
		2.5	.34	.31	.28	.25	.23	.22	.15	.15
		3.0	.36	.33	.31	.27	.25	.23	.16	.15
		4.0	.40	.37	.34	.29	.28	.26	.18	.17
	0° to 90°—6%	5.0	.41	.38	.37	.31	.29	.28	.19	.18
25	PRISMATIC ENCLOSED	0.6	.19	.15	.12	.16	.13	.10	.10	.09
		0.8	.24	.20	.17	.20	.17	.14	.14	.12
		1.0	.27	.23	.20	.23	.19	.17	.16	.14
		1.25	.31	.27	.23	.26	.22	.20	.18	.16
		1.5	.34	.29	.25	.28	.24	.22	.20	.18
	90° to 180°—57%	2.0	.38	.34	.30	.32	.28	.25	.22	.20
		2.5	.41	.37	.34	.34	.31	.28	.25	.23
		3.0	.44	.40	.36	.36	.33	.30	.26	.24
		4.0	.48	.44	.41	.40	.36	.34	.29	.27
	0° to 90°—26%	5.0	.50	.46	.43	.42	.38	.36	.30	.29
26	CLEAR TOP ENCLOSED Enameled Glass	0.6	.16	.12	.10	.13	.10	.08	.07	.06
		0.8	.20	.16	.13	.17	.13	.11	.10	.09
		1.0	.23	.19	.16	.19	.15	.13	.12	.10
		1.25	.26	.22	.19	.21	.18	.15	.14	.12
		1.5	.29	.25	.21	.24	.20	.17	.15	.13
	90° to 180°—54%	2.0	.32	.28	.25	.26	.23	.20	.18	.16
		2.5	.36	.31	.28	.29	.26	.23	.20	.18
		3.0	.38	.34	.31	.31	.28	.25	.22	.20
		4.0	.42	.38	.35	.34	.31	.29	.24	.22
	0° to 90°—21%	5.0	.44	.40	.37	.36	.33	.31	.25	.24
27	MIRRORED INDIRECT	0.6	.15	.12	.10	.11	.09	.07	.05	.04
		0.8	.18	.15	.13	.13	.11	.09	.07	.06
		1.0	.22	.19	.16	.15	.13	.11	.08	.07
		1.25	.25	.22	.19	.18	.15	.13	.09	.08
		1.5	.27	.24	.21	.20	.17	.15	.10	.09
	90° to 180°—80%	2.0	.30	.27	.25	.22	.19	.17	.11	.10
		2.5	.34	.31	.28	.24	.22	.20	.13	.12
		3.0	.36	.33	.30	.26	.24	.22	.14	.13
		4.0	.40	.37	.34	.28	.26	.24	.15	.14
	0° to 90°—0%	5.0	.42	.39	.37	.30	.28	.26	.17	.15
28	ENAMELED METAL INDIRECT	0.6	.14	.11	.10	.10	.08	.07	.04	.04
		0.8	.17	.14	.13	.13	.10	.09	.06	.05
		1.0	.20	.17	.15	.14	.12	.10	.07	.06
		1.25	.23	.20	.17	.17	.14	.13	.08	.07
		1.5	.25	.22	.19	.18	.15	.14	.09	.08
	90° to 180°—74%	2.0	.28	.25	.23	.21	.18	.16	.10	.10
		2.5	.31	.28	.26	.22	.20	.18	.12	.11
		3.0	.33	.30	.28	.24	.22	.20	.13	.12
		4.0	.37	.34	.32	.26	.24	.22	.14	.13
	0° to 90°—0%	5.0	.39	.36	.34	.28	.26	.24	.15	.14

TABLE XXXIX

SPACING — MOUNTING HEIGHT

Semi and Totally Indirect Lighting Units, No. 22 to No. 28

Ceiling Height		Permissible Spacing Distance Between Outlets	Permissible Distance Between Outlet and Sidewalls		Suspension Distance Ceiling to Top of Reflector**
Above Plane of Work (H)	Above Floor* (C)	(D)	In Usual Locations where Aisles and Storage are Next to Wall (W)	In Offices or where Work Benches are Next to Wall (W)	(R)
5	7½	7½	3½	2½	1¼
6	8½	9	4½	3	1½
7	9½	10½	5	3½	1¾
8	10½	12	6	4	2
9	11½	13½	6½	4½	2¼
10	12½	15	7½	5	2½
11	13½	16½	8	5½	2¾
12	14½	18	9	6	3
13	15½	19½	9½	6½	3¼
14	16½	21	10½	7	3½
15	17½	22½	11	7½	3¾
16	18½	24	12	8	4
18	20½	27	13½	9	4½
21	23½	31½	15½	10½	5¼
24	26½	36	18	12	6
27	29½	40½	20	13½	6¾
30	32½	45	22½	15	7½
35	37½	52½	26	17½	8¾
40	42½	60	30	20	10

* Plane of work (P) assumed to be 2½ feet above floor. When the plane of work is higher or lower than 2½ feet above floor, neglect column (C) and work from column (H).

** Suspension distances (R) in Table are based on best distribution of light and efficiency of utilization for standard units. In some installations other considerations may require a different suspension distance.

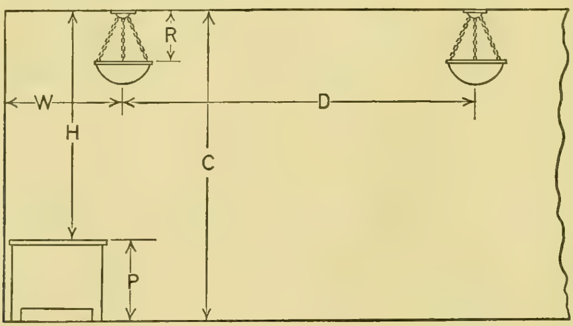


FIG. 113.

TABLE XL

Spacing — Mounting Height

Direct Lighting Units, Including Semi-enclosing and Totally Enclosing Units, No. 1 to No. 21

Mounting Height of Unit		Permissible Distance Between Outlets	Permissible Distance Between Outlets and Sidewalls	
Above Plane of Work (H)	Above Floor* (F)	(D)	In Usual Locations where Aisles and Storage are Next to Wall (W)	In Offices or where Work Benches are Next to Wall (W)
4	6½	6	3	2
5	7½	7½	3½	2½
6	8½	9	4½	3
7	9½	10½	5	3½
8	10½	12	6	4
9	11½	13½	6½	4½
10	12½	15	7½	5
11	13½	16½	8	5½
12	14½	18	9	6
13	15½	19½	9½	6½
14	16½	21	10½	7
15	17½	22½	11	7½
16	18½	24	12	8
18	20½	27	13½	9
20	22½	30	15	10
22	24½	33	16½	11
24	26½	36	18	12
27	29½	40½	20	13½
30	32½	45	22½	15
35	37½	52½	26	17½
40	42½	60	30	20

* Plane of work (P) assumed to be 2½ feet above floor. When the plane of work is higher or lower than 2½ feet above floor, neglect column (F) and work from column (H).

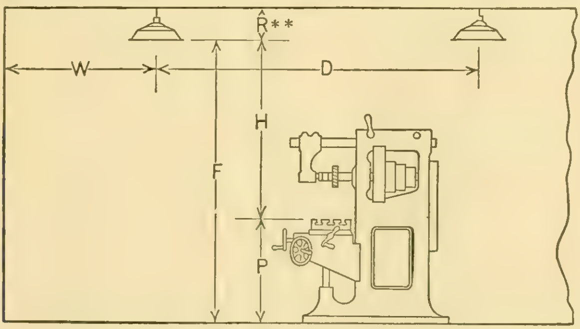


Fig. 114.

** Minimum allowance for (R) usually 1 foot.

Maintenance. — Dirty reflectors, walls and ceilings darkened by smoke and dust, blackened lamps left in service as long as they continue to burn, empty sockets, unobserved burn-outs and replacements with lamps of wrong size or improper voltage rating are prime causes of inadequate illumination.

There are two methods by which the maintenance of any selected value of intensity can be assured: First, by allowing for an enormous depreciation in the light and consequently using much larger lamps than would ordinarily be considered necessary; and second, by maintaining the system properly and allowing for reasonable depreciation. The second, or practical, method involves:

1. The use of a depreciation factor, or factor of safety, in the original design of the system to insure adequate illumination when the system has depreciated a normal amount;
2. The cleaning of lighting units at frequent regular intervals;
3. The replacement of lamps which have become blackened in service by abnormally long life;
4. The use of lamps of the correct voltage rating for all replacements;
5. The refinishing of ceilings and walls at reasonable intervals.

The purpose of the depreciation factor is to insure adequate illumination when the installation shows maximum depreciation under the system of cleaning adopted. For example, where units are cleaned and inspected every three weeks, the illumination just before cleaning may be 15 per cent lower than immediately after. Furthermore, the ceiling and walls will gradually become darkened, so that the illumination at the end of a year, even with the lighting units thoroughly cleaned and the lamps in excellent condition, will be materially lower than when the installation was new. In order to insure that the illumination will at no time be inadequate, it is necessary to add a suitable amount to the intensity considered desirable and to design for this larger amount.

The amount which should be added to the intensity considered adequate, or — what amounts to the same thing — the factor by which the intensity considered adequate should be multiplied, to insure proper illumination at all times, depends upon the specific conditions surrounding any particular installation. In general, when installed in relatively favorable locations, open reflector units show a depreciation which ranges from 10 per cent to 25 per cent in four weeks' time. Where excessive smoke and dust are the rule, the depreciation over the same period may be as high as 40 per cent. The depreciation of ceilings and walls depends not only upon the characteristics of the location, i.e., whether clean or dirty, but upon their original color as well. The only

factor which is not affected by location is the depreciation of lamps with burning. Gas-filled tungsten lamps average about 95 per cent of their initial light output throughout life; the output at the end of rated life is usually about 92 per cent of initial and where there are only one or two lamps in a room, lamp depreciation must be based upon this figure rather than upon the average output. While the total depreciation of lighting systems over a given period will, of course, vary widely, experience has shown that a factor of 1.2 for very clean locations and very clean operations ($16\frac{2}{3}$ per cent loss), and a factor of 1.5 for dirty locations and relatively dirty operations ($33\frac{1}{3}$ per cent loss), may be used with assurance of satisfactory results, *provided — and this is of the greatest importance — that a schedule of regular and frequent cleaning be adopted and adhered to.*

Designing a Lighting System

The four steps to be carried out in the design of a general lighting system for a room are as follows:

1. Decide the foot-candle illumination required;
2. Select the type of lighting unit best adapted to the location;
3. Determine the location of outlets, the mounting height and number of lighting units required;
4. Ascertain the size of lamp which will provide the foot-candles desired.

Foot-candle Illumination. — The factors entering into the choice of foot-candle illumination values have already been discussed, and Table XXXII lists such foot-candle values, corresponding to present standards for different classes of industrial lighting, offices, stores, etc.

It must be borne in mind that one sees an object because of the light incident upon it. The following charts, which show the reflection factors of different colored surfaces, show why a given operation on dark-colored cloth will require perhaps five times as much light as the same operation on light-colored goods.

Type of Lighting Unit. — These colored charts, entitled "Reflection Factors," will be found to be of assistance in selecting the proper lighting unit for a particular location in accordance with the general principles outlined in the previous section.

It is important in every case to specify the type of lamp to be used since, for example, as shown in Table XXXV, bowl-enameled lamps used in open reflectors, such as R L M standard domes, form a much superior lighting unit, from the standpoint of glare, reflected glare, and shadows, to clear-lamp units of the same type. In general, clear gas-

filled tungsten lamps should not be used in open reflectors where the mounting height is less than 20 feet.

Location of Outlets, Mounting Height, and Number of Lighting Units. — Make a diagram to scale of the floor area of the room. If the units are of semi- or totally-indirect type, measure the ceiling height of room and refer to Table XXXIX, Fig. 113, for the permissible spacing of units and preferred suspension distance of lighting units corresponding to this ceiling height.

If the units are of direct-lighting type, determine the mounting height and refer to Table XL, Fig. 114, for the permissible spacing corresponding to this mounting height. If the units are mounted as close to the ceiling as possible (a minimum allowance of 1 foot is usually necessary to provide for the drop of the reflector from the ceiling) a wider spacing is permissible and fewer units are, therefore, necessary for an even distribution of light. Considerations of shadows, appearance and arrangement of work may make a lesser mounting height desirable even though a closer spacing of outlets would be needed to keep the same uniformity of illumination. Ordinarily, lamps should not be mounted less than 10 feet above the floor unless a low ceiling makes it necessary.

Having determined the permissible spacing, proceed to locate the outlets on the diagram of the floor area. Locate the units as nearly symmetrically as possible without appreciably exceeding the permissible spacing for uniform illumination. At a greater height, a spacing closer than in Table XXXIX results in greater freedom from shadows but increases the number of units required and makes the installation cost more. If a spacing somewhat closer than the permissible value is adopted, as is often the case, it is allowable, though not necessary, to refer back to Table XXXIX and select a lower mounting height corresponding to the new spacing. The distance between the outside row of outlets and the wall should not exceed one-half the spacing distance. For office spaces, or where work is carried on at benches or machines near the wall, this distance should be approximately one-third the spacing distance.

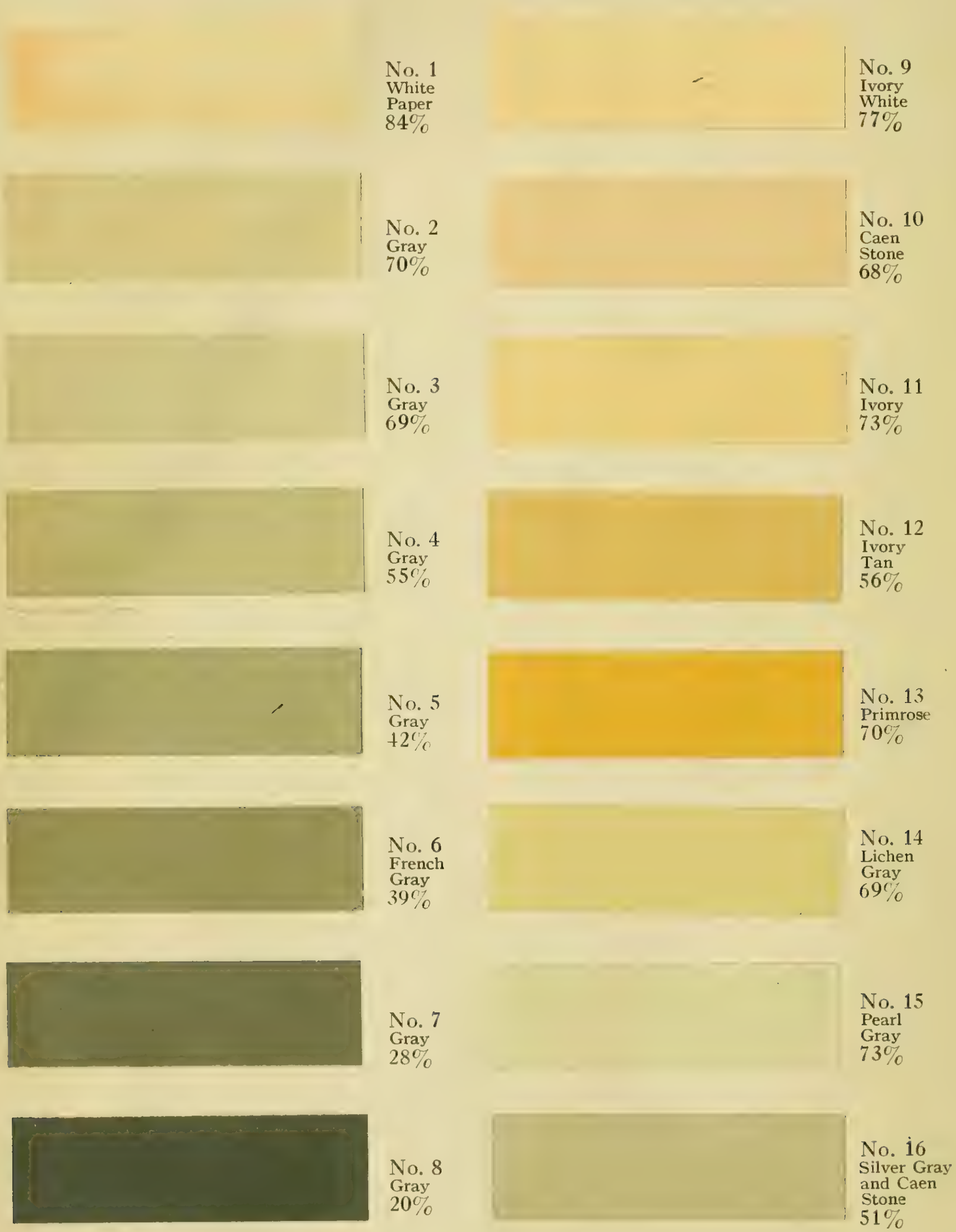
Lamp Size. — After the outlets have been located on the plan, the lamp size to be used may be determined by the following calculation:

$$(A) \qquad \frac{\text{Area in square feet}}{\text{per outlet}} = \frac{\text{Total floor area in square feet}}{\text{Number of outlets}}$$

$$(B) \qquad \frac{\text{Lamp lumens required}}{\text{per square foot}} = \frac{\text{Foot-candles} \times \text{depreciation factor}}{\text{Coefficient of utilization}}$$

Reflection Factors

The proportion of light reflected by walls and ceilings of various colors, that is, their Reflection Factors, have an important bearing on both the natural and the artificial lighting. The proportion reflected will depend somewhat upon the color of the incident light. The figures here given show what proportion of



# of Colored Surfaces

the light of MAZDA lamps these painted surfaces reflect. Reflection Factors are of special usefulness in determining the Coefficient of Utilization (ratio of light delivered at the work to total light of lamps) applicable to an interior. The Reflection Factor of any colored surface can be approximated by comparing it with these samples.

No. 17
Buff Stone and Pale Azure
37%

No. 18
Buff
60%

No. 19
Buff Stone
47%

No. 20
Tan
28%

No. 21
Cocoanut Brown
16%

No. 22
Satin Green
63%

No. 23
Bright Sage and Ivory Tan
43%

No. 24
Bright Sage
38%

No. 25
Forest Green
16%

No. 26
Olive Green
21%

No. 27
Pale Azure and White
52%

No. 28
Pale Azure
39%

No. 29
Sky Blue
36%

No. 30
Shell Pink
51%

No. 31
Pink
50%

No. 32
Cardinal Red
16%

$$(C)\quad \begin{array}{c}\text{Lamp lumens required}\\ \text{per outlet}\end{array} = \begin{array}{c}\text{Area in sq. ft.}\\ \text{per outlet}\\ \text{(From } A\text{)}\end{array} \times \begin{array}{c}\text{Lamp lumens required}\\ \text{per square foot}\\ \text{(From } B\text{)}\end{array}$$

Foot-candles. — Illumination decided upon.

Depreciation Factor. — Safety factor or allowance for depreciation due to aging of lamps, dirt, dust and deterioration of reflecting value of walls. Use 1.3 for fairly clean locations. Use 1.5 for dirty locations or where cleaning is infrequent.

Coefficient of Utilization. — Proportion of the generated light from the lamps which reaches the plane of work. The coefficient of utilization for the installation is determined as follows:

Table XXXVIII shows that the coefficient of utilization varies according to the type of fixture, the proportions of the room expressed by " room index," and the color of the walls and ceiling. From Table XXXVII find the room index corresponding most nearly to the dimensions of the installation. From the color chart find the reflection factor of the walls and ceiling of the room under consideration. Then the coefficient of utilization for the installation of the type of lighting unit selected will be found from Table XXXVIII in the proper column of wall and ceiling color opposite the correct room index.

Having determined the lamp lumens required per outlet by the above calculations, find the wattage of the lamps to be used, by reference to Table XLI which lists the lumen output rating for each size of tungsten and tungsten daylight lamps. Locate in this table the size of lamp of the desired type which most nearly meets the requirement of lumen output. When the lamp lumens required fall nearly midway between two sizes, choose the larger rather than the smaller, unless it is certain that the less illumination from the smaller will suffice.

Computed Illumination Values. — The foot-candles of illumination in service, allowing a depreciation factor of 1.3, obtained for systems having different coefficients of utilization and areas per lamp, are worked out in Table XLII. This table can be referred to as an approximate check on design computations made as outlined above.

Illumination Design for a Factory Room. — The floor plan of the factory space to be lighted is 60 by 120 feet, as shown (Fig. 115). The work carried on in the room is assembly of sewing machine heads. The height from floor to roof trusses is 12 feet. The roof is of saw-tooth construction and the walls and upper structure are painted a medium color. A considerable amount of dark material is kept stacked along the walls of the room. Following the steps outlined, the lighting design is determined as follows:

1. *Foot-candle Illumination.* — From Table XXXII, 8 foot-candles are recommended for assembly, medium grade.

2. *Type of Lighting Unit.* — With the aid of the guide to the selection of reflecting equipment (Table XXXIII), unit No. 2, the R L M dome with bowl-enameled lamp, is selected, this selection being based on efficiency and favorable showing from the standpoints of glare, reflected glare, shadows and maintenance.

3. *Location of Outlets, Mounting Height and Number of Units.* — The height of the benches, and therefore the plane of work, is $3\frac{1}{2}$ feet above the floor. The maximum mounting height of the lamps above the floor is 11 feet (12 feet height from floor to truss less 1 foot allowed

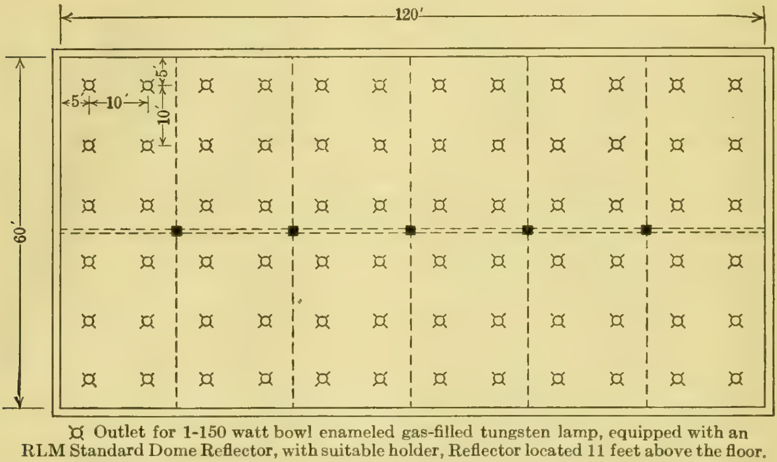


FIG. 115. Floor Plan of Factory Space to be lighted.

for reflector drop). Hence, the maximum mounting height of units above plane of work is 11 feet $- 3\frac{1}{2}$, or $7\frac{1}{2}$ feet.

From Table XL of spacing-mounting heights, page 303, a $7\frac{1}{2}$-foot mounting height above plane for direct lighting units is found to indicate a permissible spacing of approximately 11 feet, and since the section of the room near the walls consists of aisles and storage, $5\frac{1}{2}$ feet may be allowed for the distance between the last row of outlets and the side walls.

Reference to floor plan of the room shows that a 10-foot spacing each way (outside units 5 feet from walls) would make a symmetrical layout in the 20 by 30-foot bays and this spacing is, therefore, adopted. Outlet locations for the entire space are marked on the plan as shown, and 72 are found to be required.

TABLE XLI

Approximate Lumen Output of Tungsten Lamps

Size of Lamp in Watts	110–125 Volt Standard Lighting Service			220–225 Volt	
	Gas-filled	Vacuum	Daylight	Gas-filled	Vacuum
	Lumen Output				
10	......	80	......	......	......
15	......	130	......	......	......
25	......	240	......	......	195
40	......	400	......	......	......
50	450*	500	......	......	450
60	......	620	......	......	......
75	880	......	600	......	......
100	1,300	......	875	980	945
150	2,100	......	1400	......	......
200	3,000	......	2000	2,500	......
300	4,900	......	3360	4,300	......
500	9,000	......	5600	7,800	......
750	14,500	......	......	12,500	......
1000	20,000	......	......	18,000	......

* White bulb.

4. Lamp size:

(*A*) $$\text{Area in sq. ft. per outlet} = \frac{\text{Total floor area in sq. ft.}}{\text{Number of outlets in room}} = \frac{7200}{72} = 100.$$

(*B*) $$\text{Lamp lumens required per sq. ft.} = \frac{\text{Foot-candles} \times \text{depreciation factor}}{\text{Coefficient of utilization}} = \frac{8 \times 1.30}{.57} = 18.2.$$

Area in square feet per outlet — 100.
Foot-candles — 8.
Depreciation factor — 1.30.
To find coefficient of utilization:

From room index, Table XXXVII, page 297, in a room 60 by 120 feet where the mounting height of direct-lighting units above plane of work is 7 feet, the room index is 5.0, or in the same room where the mounting height is 8 feet the room index is 4.0. Either value might be used for the room index with equal accuracy as to the result, but 4.0 is more conservative.

TABLE XLII

Computed Illumination Values (Using Depreciation Factor of 1.3)

Area in Square Ft. per Lamp	Size of Lamp		Coefficient of Utilization															
			.14	.16	.18	.20	.22	.25	.28	.32	.36	.40	.45	.50	.55	.60	.65	**.70**
	Watts	Lumens	Foot-candles															
60	100	1300	2.3	2.7	3.0	3.3	3.7	4.2	4.7	5.3	6.0	6.7	7.5	8.3	9.2	10.0	10.8	**11.7**
	150	2100	3.8	4.3	4.8	5.4	5.9	6.7	7.5	8.6	9.7	10.8	12.1	13.5	14.8	16.2	17.5	**18.8**
	200	3100	5.6	6.4	7.2	7.9	8.7	9.9	11.1	12.7	14.3	15.9	17.9	19.9	21.8	23.8	25.8	**27.8**
	300	4900	8.8	10.0	11.3	12.6	13.8	15.7	17.6	20.1	22.6	25.1	28.3	31.4	34.6	37.7	40.8	**44.0**
70	100	1300	2.0	2.3	2.6	2.9	3.1	3.6	4.0	4.6	5.1	5.7	6.4	7.1	7.9	8.6	9.3	**10.0**
	150	2100	3.2	3.7	4.2	4.6	5.1	5.8	6.5	7.4	8.3	9.2	10.4	11.5	12.7	13.8	15.0	**16.2**
	200	3100	4.8	5.4	6.1	6.8	7.5	8.5	9.5	10.9	12.3	13.6	15.3	17.0	18.7	20.4	22.1	**23.8**
	300	4900	7.5	8.6	9.7	10.8	11.8	13.5	15.1	17.2	19.4	21.5	24.2	26.9	29.6	32.3	35.0	**37.7**
80	100	1300	1.8	2.0	2.2	2.5	2.8	3.1	3.5	4.0	4.5	5.0	5.6	6.2	6.9	7.5	8.1	**8.7**
	150	2100	2.8	3.2	3.6	4.0	4.4	5.0	5.7	6.5	7.3	8.1	9.1	10.1	11.1	12.1	13.1	**14.1**
	200	3100	4.2	4.8	5.4	6.0	6.6	7.4	8.3	9.5	10.7	11.9	13.4	14.9	16.4	17.9	19.4	**20.9**
	300	4900	6.6	7.5	8.5	9.4	10.4	11.9	13.2	15.1	17.0	18.8	21.2	23.6	25.9	28.3	30.6	**33.0**
90	100	1300	1.6	1.8	2.0	2.2	2.4	2.8	3.1	3.6	4.0	4.5	5.0	5.6	6.1	6.7	7.2	**7.8**
	150	2100	2.5	2.9	3.2	3.6	3.9	4.5	5.0	5.7	6.5	7.2	8.1	9.0	9.9	10.8	11.7	**12.6**
	200	3100	3.7	4.2	4.8	5.3	5.8	6.6	7.4	8.5	9.5	10.6	11.9	13.2	14.5	15.9	17.2	**18.5**
	300	4900	5.9	6.7	7.5	8.4	9.2	10.5	11.7	13.4	15.1	16.8	18.8	20.9	23.0	25.1	27.2	**29.2**
100	100	1300	1.4	1.6	1.8	2.0	2.2	2.5	2.8	3.2	3.6	4.0	4.5	5.0	5.5	6.0	6.5	**7.0**
	150	2100	2.3	2.6	2.9	3.2	3.6	4.0	4.5	5.2	5.8	6.5	7.3	8.1	8.9	9.7	10.5	**11.3**
	200	3100	3.3	3.8	4.3	4.8	5.2	5.9	6.7	7.6	8.6	9.5	10.7	11.9	13.1	14.3	15.5	**16.7**
	300	4900	5.3	6.0	6.8	7.5	8.3	9.4	10.6	12.1	13.6	15.1	17.0	18.8	20.7	22.6	24.5	**26.4**
110	100	1300	1.3	1.5	1.6	1.8	2.0	2.3	2.5	2.7	3.3	3.6	4.1	4.5	5.0	5.5	5.9	**6.4**
	150	2100	2.1	2.4	2.6	2.9	3.2	3.7	4.1	4.7	5.3	5.9	6.6	7.3	8.1	8.8	9.5	**10.2**
	200	3100	3.0	3.5	3.9	4.3	4.8	5.4	6.1	6.9	7.8	8.7	9.8	10.8	11.9	13.0	14.0	**15.2**
	300	4900	4.3	5.5	6.2	6.9	7.5	8.6	9.6	11.0	12.3	13.7	15.4	17.1	18.8	20.6	22.3	**24.0**
120	100	1300	1.2	1.3	1.5	1.7	1.8	2.1	2.3	2.7	3.0	3.3	3.8	4.2	4.6	5.0	5.4	**5.8**
	150	2100	1.9	2.2	2.4	2.7	3.0	3.4	3.8	4.3	4.8	5.4	6.1	6.7	7.4	8.1	8.8	**9.4**
	200	3100	2.8	3.2	3.6	4.0	4.4	5.0	5.6	6.3	7.1	7.9	8.9	9.9	11.0	12.0	13.0	**14.0**
	300	4900	4.4	5.0	5.7	6.3	6.9	7.9	8.8	10.1	11.3	12.6	14.1	15.7	17.3	18.8	20.4	**22.0**
130	100	1300	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.5	2.8	3.1	3.5	3.8	4.2	4.6	5.0	**5.4**
	150	2100	1.7	2.0	2.2	2.5	2.7	3.1	3.5	4.0	4.5	5.0	5.6	6.2	6.8	7.5	8.1	**8.7**
	200	3100	2.6	2.9	3.3	3.7	4.0	4.5	5.1	5.9	6.6	7.4	8.3	9.2	10.1	11.0	11.9	**12.8**
	300	4900	4.1	4.6	5.2	5.8	6.4	7.2	8.1	9.3	10.4	11.6	13.1	14.5	16.0	17.4	18.9	**20.3**
140	100	1300	1.0	1.1	1.3	1.4	1.6	1.8	2.0	2.3	2.6	2.9	3.2	3.6	3.9	4.3	4.6	**5.0**
	150	2100	1.6	1.8	2.1	2.3	2.5	2.9	3.2	3.7	4.2	4.6	5.2	5.8	6.3	6.9	7.5	**8.1**
	200	3100	2.4	2.7	3.1	3.4	3.8	4.3	4.8	5.5	6.1	6.8	7.7	8.5	9.4	10.2	11.1	**11.9**
	300	4900	3.8	4.3	4.9	5.4	5.9	6.7	7.5	8.6	9.7	10.8	12.1	13.5	14.8	16.2	17.5	**18.8**
160	150	2100	1.4	1.6	1.8	2.0	2.2	2.5	2.8	3.2	3.6	4.0	4.5	5.0	5.6	6.1	6.6	**7.1**
	200	3100	2.1	2.4	2.7	3.0	3.3	3.7	4.2	4.8	5.4	5.9	6.7	7.4	8.2	8.9	9.7	**10.5**
	300	4900	3.3	3.8	4.2	4.7	5.2	5.9	6.6	7.5	8.5	9.4	10.6	11.8	13.0	14.1	15.3	**16.5**
	500	8800	5.9	6.8	7.6	8.5	9.3	10.6	11.8	13.5	15.2	16.9	19.0	21.2	23.3	25.4	27.5	**29.6**
180	150	2100	1.3	1.4	1.6	1.8	2.0	2.2	2.5	2.9	3.2	3.6	4.0	4.5	4.9	5.4	5.8	**6.3**
	200	3100	1.8	2.1	2.4	2.6	2.9	3.3	3.7	4.2	4.8	5.3	5.9	6.6	7.3	7.9	8.6	**9.3**
	300	4900	2.9	3.4	3.8	4.2	4.6	5.2	5.9	6.7	7.5	8.4	9.4	10.5	11.5	12.6	13.6	**14.7**
	500	8800	5.3	6.0	6.8	7.5	8.3	9.4	10.5	12.0	13.5	15.0	16.9	18.8	20.7	22.6	24.4	**26.3**
200	150	2100	1.1	1.3	1.5	1.6	1.8	2.0	2.3	2.6	2.9	3.2	3.6	4.0	4.4	4.8	5.3	**5.7**
	200	3100	1.7	1.9	2.1	2.4	2.6	3.0	3.3	3.8	4.3	4.8	5.3	6.0	6.5	7.1	7.7	**8.3**
	300	4900	2.6	3.0	3.4	3.8	4.1	4.7	5.3	6.0	6.8	7.5	8.5	9.4	10.4	11.3	12.3	**13.2**
	500	8800	4.7	5.4	6.1	6.8	7.4	8.5	9.5	10.8	12.2	13.5	15.2	16.9	18.6	20.3	22.0	**23.7**
220	150	2100	1.0	1.2	1.3	1.5	1.6	1.8	2.1	2.4	2.6	2.9	3.3	3.7	4.0	4.4	4.8	**5.1**
	200	3100	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.5	3.9	4.3	4.9	5.4	5.9	6.5	7.0	**7.5**
	300	4900	2.4	2.7	3.1	3.4	3.8	4.3	4.8	5.5	6.2	6.9	7.7	8.6	9.4	10.3	11.1	**12.0**
	500	8800	4.3	4.9	5.5	6.2	6.8	7.7	8.6	9.8	11.1	12.3	13.8	15.4	16.9	18.5	20.0	**21.5**
250	200	3100	1.3	1.5	1.7	1.9	2.1	2.4	2.7	3.1	3.4	3.8	4.3	4.8	5.2	5.7	6.2	**6.7**
	300	4900	2.1	2.4	2.7	3.0	3.3	3.8	4.2	4.8	5.4	6.0	6.8	7.5	8.3	9.0	9.8	**10.6**
	500	8800	3.8	4.3	4.9	5.4	6.0	6.8	7.6	8.7	9.7	10.8	12.2	13.5	14.9	16.2	17.6	**18.9**
	750	14000	6.0	6.9	7.8	8.6	9.5	10.8	12.1	13.8	15.5	17.2	19.4	21.5	23.7	25.8	28.0	**30.2**
280	200	3100	1.2	1.4	1.5	1.7	1.9	2.1	2.4	2.7	3.1	3.4	3.8	4.3	4.7	5.1	5.5	**6.0**
	300	4900	1.9	2.2	2.4	2.7	3.0	3.4	3.8	4.3	4.8	5.4	6.1	6.7	7.4	8.1	8.8	**9.4**
	500	8800	3.4	3.9	4.4	4.8	5.3	6.0	6.8	7.7	8.7	9.7	10.9	12.1	13.3	14.5	15.7	**16.9**
	750	14000	5.4	6.2	6.9	7.7	8.5	9.6	10.8	12.3	13.8	15.4	17.3	19.2	21.2	23.1	25.0	**26.9**

TABLE XLII. — *Continued*

Area in Square Ft. per Lamp	Size of Lamp		Coefficient of Utilization															
			.14	.16	.18	.20	.22	.25	.28	.32	.36	.40	.45	.50	.55	.60	.65	.70
	Watts	Lumens	Foot-candles															
320	200	3100	1.0	1.2	1.3	1.5	1.6	1.9	2.1	2.4	2.7	3.0	3.4	3.7	4.1	4.5	4.9	5.2
	300	4900	1.6	1.9	2.1	2.4	2.6	2.9	3.3	3.8	4.2	4.7	5.3	5.9	6.5	7.1	7.7	8.2
	500	8800	3.0	3.4	3.8	4.2	4.7	5.3	5.9	6.8	7.6	8.5	9.5	10.6	11.6	12.7	13.8	14.8
	750	14000	4.7	5.4	6.1	6.7	7.4	8.4	9.4	10.8	12.1	13.5	15.1	16.8	18.5	20.2	21.9	23.6
360	200	3100	0.9	1.1	1.2	1.3	1.5	1.7	1.9	2.1	2.4	2.7	3.0	3.3	3.6	4.0	4.3	4.6
	300	4900	1.5	1.7	1.9	2.1	2.3	2.6	2.9	3.4	3.8	4.2	4.7	5.2	5.8	6.3	6.8	7.3
	500	8800	2.6	3.0	3.4	3.8	4.1	4.7	5.3	6.0	6.8	7.5	8.5	9.4	10.3	11.3	12.2	13.2
	750	14000	4.2	4.8	5.4	6.0	6.6	7.5	8.4	9.6	10.8	12.0	13.5	15.0	16.4	18.0	19.4	20.9
400	200	3100	0.8	0.9	1.1	1.2	1.3	1.5	1.7	1.9	2.1	2.4	2.7	3.0	3.3	3.6	3.9	4.2
	300	4900	1.3	1.5	1.7	1.9	2.1	2.4	2.6	3.0	3.4	3.8	4.2	4.7	5.2	5.7	6.1	6.6
	500	8800	2.4	2.7	3.0	3.4	3.7	4.2	4.7	5.4	6.1	6.8	7.6	8.5	9.3	10.2	11.0	11.8
	750	14000	3.8	4.3	4.8	5.4	5.9	6.7	7.5	8.6	9.7	10.8	12.1	13.5	14.8	16.2	17.5	18.8
450	200	3100	0.7	0.8	1.0	1.1	1.2	1.3	1.5	1.7	1.9	2.1	2.4	2.6	2.9	3.2	3.5	3.7
	300	4900	1.2	1.3	1.5	1.7	1.8	2.1	2.3	2.7	3.0	3.4	3.8	4.2	4.6	5.0	5.4	5.9
	500	8800	2.1	2.4	2.7	3.0	3.3	3.8	4.2	4.8	5.4	6.0	6.8	7.5	8.3	9.0	9.8	10.5
	750	14000	3.4	3.8	4.3	4.8	5.3	6.0	6.7	7.7	8.6	9.6	10.8	12.0	13.2	14.4	15.6	16.8
500	300	4900	1.1	1.2	1.4	1.5	1.7	1.9	2.1	2.4	2.7	3.0	3.4	3.8	4.1	4.5	4.9	5.3
	500	8800	1.9	2.2	2.4	2.7	3.0	3.4	3.8	4.3	4.9	5.4	6.1	6.8	7.4	8.1	8.8	9.5
	750	14000	3.0	3.4	3.9	4.3	4.7	5.4	6.0	6.9	7.8	8.6	9.7	10.9	11.9	12.9	14.0	15.1
	1000	20000	4.3	4.9	5.5	6.2	6.8	7.7	8.6	9.8	11.1	12.3	13.8	15.4	16.9	18.4	20.0	21.5
600	300	4900	0.9	1.0	1.1	1.3	1.4	1.6	1.8	2.0	2.3	2.5	2.8	3.1	3.5	3.8	4.1	4.4
	500	8800	1.6	1.8	2.0	2.3	2.5	2.8	3.2	3.6	4.1	4.5	5.1	5.6	6.2	6.8	7.3	7.9
	750	14000	2.5	2.9	3.2	3.6	4.0	4.5	5.0	5.7	6.5	7.2	8.1	9.0	9.9	10.8	11.7	12.6
	1000	20000	3.6	4.1	4.6	5.1	5.6	6.4	7.2	8.2	9.2	10.3	11.5	12.8	14.1	15.4	16.7	18.0
700	300	4900	0.8	0.9	1.0	1.1	1.2	1.3	1.5	1.7	1.9	2.2	2.4	2.7	2.0	3.2	3.5	3.8
	500	8800	1.4	1.5	1.7	1.9	2.1	2.4	2.7	3.1	3.5	3.9	4.4	4.8	5.3	5.8	6.3	6.8
	750	14000	2.2	2.5	2.8	3.1	3.4	3.8	4.3	4.9	5.5	6.2	6.9	7.7	8.5	9.2	10.0	10.8
	1000	20000	3.1	3.5	4.0	4.4	4.8	5.5	6.2	7.0	7.9	8.8	9.9	11.0	12.1	13.2	14.3	15.4
800	300	4900	0.7	0.8	0.8	0.9	1.0	1.2	1.3	1.5	1.7	1.9	2.1	2.4	2.6	2.8	3.1	3.3
	500	8800	1.2	1.4	1.5	1.7	1.9	2.1	2.4	2.7	3.0	3.4	3.8	4.2	4.7	5.1	5.5	5.9
	750	14000	1.9	2.2	2.4	2.7	3.0	3.4	3.8	4.3	4.8	5.4	6.1	6.7	7.4	8.1	8.8	9.4
	1000	20000	2.7	3.1	3.5	3.8	4.2	4.8	5.4	6.2	6.9	7.7	8.7	9.6	10.6	11.5	12.5	13.5
900	300	4900	0.6	0.7	0.8	0.8	0.9	1.0	1.2	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9
	500	8800	1.1	1.2	1.4	1.5	1.7	1.9	2.1	2.4	2.7	3.0	3.4	3.8	4.1	4.5	4.9	5.3
	750	14000	1.7	1.9	2.2	2.4	2.6	3.0	3.4	3.8	4.3	4.8	5.4	6.0	6.6	7.2	7.8	8.4
	1000	20000	2.4	2.7	3.1	3.4	3.8	4.3	4.8	5.5	6.2	6.8	7.7	8.6	9.4	10.3	11.1	12.0
1000	300	4900	0.5	0.6	0.7	0.8	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.1	2.3	2.4	2.6
	500	8800	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.4	3.7	4.1	4.4	4.7
	750	14000	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.4	3.9	4.3	4.8	5.4	5.9	6.5	7.0	7.5
	1000	20000	2.2	2.5	2.8	3.1	3.4	3.8	4.3	4.9	5.5	6.2	6.9	7.7	8.5	9.2	10.0	10.8
1200	300	4900	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.6	1.7	1.9	2.0	2.2
	500	8800	0.8	0.9	1.0	1.1	1.2	1.4	1.6	1.8	2.0	2.3	2.5	2.8	3.1	3.4	3.7	3.9
	750	14000	1.3	1.4	1.6	1.8	2.0	2.2	2.5	2.9	3.2	3.6	4.0	4.5	4.9	5.4	5.8	6.3
	1000	20000	1.8	2.1	2.3	2.6	2.8	3.2	3.6	4.1	4.6	5.1	5.8	6.4	7.1	7.7	8.3	9.0
1400	300	4900	0.4	0.4	0.5	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.5	1.6	1.8	1.9
	500	8800	0.7	0.8	0.9	1.0	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.4	2.7	2.9	3.1	3.4
	750	14000	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.5	2.8	3.1	3.5	3.8	4.2	4.6	5.0	5.4
	1000	20000	1.5	1.8	2.0	2.2	2.4	2.7	3.1	3.5	4.0	4.4	4.9	5.5	6.0	6.6	7.1	7.7
1600	300	4900	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.1	1.2	1.3	1.4	1.5	1.6
	500	8800	0.6	0.7	0.8	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.1	2.3	2.5	2.8	3.0
	750	14000	0.9	1.1	1.2	1.3	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.4	3.7	4.0	4.4	4.7
	1000	20000	1.3	1.5	1.7	1.9	2.1	2.4	2.7	3.1	3.5	3.8	4.3	4.8	5.3	5.8	6.2	6.7
2000	300	4900	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.2	1.3
	500	8800	0.5	0.5	0.6	0.7	0.7	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.0	2.2	2.4
	750	14000	0.8	0.9	1.0	1.1	1.2	1.3	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.2	3.5	3.8
	1000	20000	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.5	2.8	3.1	3.5	3.8	4.2	4.6	5.0	5.4
2500	300	4900	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1
	500	8800	0.4	0.4	0.5	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.4	1.5	1.6	1.8	1.9
	750	14000	0.6	0.7	0.8	0.9	0.9	1.1	1.2	1.4	1.6	1.7	1.9	2.2	2.4	2.6	2.8	3.0
	1000	20000	0.9	1.0	1.1	1.2	1.4	1.5	1.7	2.0	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.3

Referring to Table XXXVIII, coefficients of utilization, page 298, for R L M dome bowl-enameled lamps in a location with a room index of 4.0 and where the ceiling and walls are fairly dark, the coefficient of utilization is found to be .57.

Combining (*A*) and (*B*):

(*C*) Lamp lumens required per outlet = Area in sq. ft. per outlet × Lamp lumens required per sq. ft.
$= 100 \times 18.2 = 1820.$

From Table XLI lumen output of tungsten lamps, page 309, a 150-watt gas-filled lamp giving 2100 lumens is found to meet the requirement most nearly. The actual service illumination given by this lamp will, of course, be slightly greater than originally designed for, or

$$\frac{2100}{1820} \times 8 = 9.2 \text{ foot-candles.}$$

As an approximate check on the computation, reference may be made to Table XLII where, with a coefficient of utilization of 0.55 (the table value nearest to 0.57) and an area per lamp of 100 square feet, the illumination, using 150-watt gas-filled lamps, is found to be 8.6 foot-candles.

Choice of Reflecting Equipment. — The various lighting units in Table XXXIII are rated in accordance with seven fundamentals, illustrated on the following page. The importance of these criteria varies with different classes of work. It must be emphasized that the relative importance of the various criteria should be carefully weighed with respect to the particular problem at hand. For instance, in an office the criteria would rank in the following order of importance: (1) direct glare; (2) reflected glare; (3) shadows; (4) efficiency, based upon illumination on horizontal; (5) maintenance; (6) vertical illumination. On the other hand, where lamps are to be hung above a crane in a foundry, the order of importance would be as follows: (1) efficiency based upon illumination on horizontal; (2) vertical illumination; (3) maintenance; (4) shadows; (5) direct glare; (6) reflected glare.

In the chart (Table XXXIII) the best rating given is A^+, which denotes the highest degree of excellence; while *D*, the lowest, indicates that an installation of units so rated with respect to any factor will be very likely to prove unsatisfactory if this factor is important in the given installation. The ratings *B* and *C*, while indicating a result not equal to *A*, are decidedly superior to rating *D*. In other words, a rating of *B*, C^+ or *C* in certain respects does not disqualify a unit, provided that in the essential requirements of the given location the unit is rated *A* or B^+.

A^+		B^+		C^+		
A	Excellent	B	Good	C	Fair	D Very bad
A^-		B^-		C^-		

Cost of Light

Estimating the Cost. — In determining the total operating cost of any system of lighting, three items should be considered:

1. Fixed charges, which include interest on the investments, insurance and taxes, depreciation of permanent parts, regular attendance, and other expenses which are independent of the number of hours of use. Often this item forms a large part of the total operating expense; yet it is only too frequently omitted from cost tables.
2. Maintenance charges, which include renewal of parts, labor and all costs, except the cost of energy, which depends upon the hours of burning.
3. The cost of energy, which depends upon the hours of burning and the rate charged.

If data are compiled under these heads in convenient units — for example, under the first head, an annual charge; under the second, a charge per 1000 hours' operation; under the third, a charge per 1000 hours' operation at unit cost of energy — the several items may easily be calculated for any given set of conditions and the total annual operating cost of any lighting system obtained as their sum.

Under fixed charges, the items of depreciation and attendance may be mentioned particularly. Depreciation should be charged on permanent parts only, and not upon parts the renewal of which is provided for in the maintenance cost. The rate for depreciation should in many cases be higher than the current practice, for obsolescence, rather than the wearing out of parts, determines the life of a lighting system. There are many installations in use today which are in good order and giving a fair measure of satisfaction, but which could be replaced at a large saving. In fact, there are few installations in this country which have been in use for seven or eight years and which are not practically obsolete.

Again, too much emphasis cannot be given to the desirability of regular attendance for those illuminants which do not require trimming from time to time. As has been said, it is essential for satisfactory operation that such lamps and reflectors be cleaned at regular intervals; hence a fixed charge should always be included in this service. Lamps which require frequent trimming are cleaned at the same time, and the cost is included under the maintenance charge.

The energy cost can usually be readily computed, but will, in the case of some electric illuminants, depend upon the voltage of the circuit, since this determines either the wattage or the power-factor. The effect of power-factor is seldom considered, although it governs the investment in generators, transformers and wiring, and in a small degree the energy required. To the central station or isolated plant, the volt-amperes required by a given lamp are perhaps as close a measure of the cost of service as the actual wattage consumed. When the consumer is purchasing energy on a kilowatt-hour basis, this factor, of course, is eliminated as far as he is concerned.

A table which would show the total operating expense of lamps of all sizes with every discount from the list prices, for all possible periods of burning per year and under all costs of power, would be so large as to be entirely impractical. From Table XLIII, however, the operating expense of incandescent lamps under any set of conditions may be found with little calculation.

In the case of an incandescent system, in addition to the wiring, the investment includes the cost of lamps, reflectors, holders and sockets. The investment in permanent parts is the total investment minus the price of lamps. No depreciation is charged against the lamps inasmuch as they are regularly renewed. The labor item under fixed charges provides for the cleaning of all units once each month. For the smaller units with steel reflectors, the cost of cleaning in Table XLIII is taken as 4.5 cents per unit for each cleaning. Data obtained from installations where accurate cost records are kept show that this figure is conservative for labor at 45 cents an hour. The cost of cleaning other reflectors is taken in proportion to the amount of labor required.

The maintenance charge is given for a 1000-hour period of burning. To find the annual charge in any case, it is necessary to multiply by the total hours of burning and to divide by 1000 hours.

The energy cost is given for a 1000-hour period, with energy at 1 cent per kilowatt-hour. The energy cost per year is found by multiplying by the time of burning in thousands of hours and the rate in cents per kilowatt-hour.

An example will illustrate the use of Table XLIII. It is required to find the total operating expense per year for lighting an erecting room. This room is lighted with 22 1000-watt, gas-filled tungsten lamps. The lamps are burned a total of 4000 hours per year and are purchased at the discount obtained on a $1200 contract. The cost of energy is 2 cents per kilowatt-hour.

TABLE XLIII

Analysis of Operating Costs — 110- to 125-Volt Tungsten Lamp Units

Lamp and Reflector Data Upon Which Costs are Calculated													
Size of Lamp, Rated Watts	Vacuum				Gas-Filled								
	25	40	50	60	75	100	150	200	300	400	500	750	1000
Cost of lamp, list*	$0.350	$0.350	$0.350	$0.400	$0.700	$1.100	$1.650	$2.200	$3.250	$4.300	$4.700	$6.500	$7.500
Cost of lamp, standard package discount†	$0.315	$0.315	$0.315	$0.360	$0.630	$0.990	$1.485	$1.980	$2.925	$3.870	$4.230	$5.850	$6.750
Average cost of reflector with socket, standard package discount	$1.700	$1.700	$1.700	$1.700	$2.200	$2.300	$2.300	$3.200	$3.800	$3.800	$3.800	$4.900	$4.900
Cost of unit, standard package discount	$2.015	$2.015	$2.015	$2.060	$2.830	$3.290	$3.785	$5.180	$6.725	$7.670	$8.030	$10.750	$11.650
Operating Costs													
Annual fixed charges:													
Interest on total investment, 6%	$0.121	$0.121	$0.121	$0.124	$0.170	$0.197	$0.227	$0.311	$0.404	$0.460	$0.482	$0.645	$0 699
Depreciation on reflector, 12½%	.213	.213	.213	.213	.275	.288	.288	.400	.475	.475	.475	.613	.613
Labor, monthly cleaning	.540	.540	.540	.540	.540	.540	.540	810	.810	1.080	1.080	1.080	1 080
Total	$0.874	$0.874	$0.874	$0.877	$0.985	$1.025	$1.055	$1.521	$1.689	$2.015	$2.037	$2.338	$2.392
Maintenance cost per 1000 hrs.:													
Lamp renewals, standard package discount	$0.315	$0.315	$0.315	$0.360	$0.630	$0.990	$1.485	$1.980	$2.925	$3.870	$4.230	$5.850	$6.750
Lamp renewals, $150 contract discount	.291	.291	.291	.332	.581	.913	1.370	1.826	2.698	3.569	3.901	5.395	6 225
Lamp renewals, $1200 contract discount	.256	.256	.256	.292	.511	.803	1.205	1.606	2.373	3.139	3.431	4.745	5.475
Energy cost per 1000 Hrs. at 1 cent per kw-hr.	$0.250	$0.400	$0.500	$0.600	$0.750	$1.000	$1.500	$2.000	$3.000	$4.000	$5.000	$7.500	$10.000

* The prices of lamps and reflectors upon which calculations of this table are based are approximate; they are used here solely for convenience in engineering calculations.

† Discounts range from 10 per cent to 40 per cent, depending upon the quantity of lamps ordered.

TABLE XLIII. — *Concluded*

TOTAL ANNUAL OPERATING COSTS — 110- TO 125-VOLT TUNGSTEN LAMP UNITS

Size of Lamp Rated Watts		Vacuum				Gas Filled								
		25	40	50	60	75	100	150	200	300	400	500	750	1000
Energy at... 1000 hours operation per year. Lamps bought on $150 contract.	1 cent	$ 1.42	$ 1.57	$ 1.67	$ 1.81	$ 2.32	$ 2.94	$ 3.93	$ 5.35	$ 7.39	$ 9.58	$10.94	$15.23	$18.62
	2 cents	1.67	1.97	2.17	2.41	3.07	3.94	5.43	7.35	10.39	13.58	15.94	22.73	28.62
	3 cents	1.92	2.37	2.67	3.01	3.82	4.94	6.93	9.35	13.39	17.58	20.94	30.23	38.62
	4 cents	2.17	2.77	3.17	3.61	4.57	5.94	8.43	11.35	16.39	21.58	25.94	37.73	48.62
	5 cents	2.42	3.17	3.67	4.21	5.32	6.94	9.93	13.35	19.39	25.58	30.94	45.23	58.62
	6 cents	2.67	3.57	4.17	4.81	6.07	7.94	11.43	15.35	22.39	29.58	35.94	52.73	68.62
	8 cents	3.17	4.37	5.17	6.01	7.57	9.94	14.43	19.35	28.39	37.58	45.94	67.73	88.62
	10 cents	3.67	5.17	6.17	7.21	9.07	11.94	17.43	23.35	34.39	45.58	55.94	82.73	108.62
Energy at... 1000 hours operation per year Lamps bought on $1200 contract.	1 cent	1.38	1.53	1.63	1.77	2.25	2.83	3.76	5.13	7.06	9.15	10.47	14.58	17.87
	2 cents	1.63	1.93	2.13	2.37	3.00	3.83	5.26	7.13	10.06	13.15	15.47	22.08	27.87
	3 cents	1.88	2.33	2.63	2.97	3.75	4.83	6.76	9.13	13.06	17.15	20.47	29.58	37.87
	4 cents	2.13	2.73	3.13	3.57	4.50	5.83	8.26	11.13	16.06	21.15	25.47	37.08	47.87
	5 cents	2.38	3.13	3.63	4.17	5.25	6.83	9.76	13.13	19.06	25.15	30.47	44.58	57.87
	6 cents	2.63	3.53	4.13	4.77	6.00	7.83	11.26	15.13	22.06	29.15	35.47	52.08	67.87
	8 cents	3.13	4.33	5.13	5.97	7.50	9.83	14.26	19.13	28.06	37.15	45.47	67.08	87.87
	10 cents	3.63	5.13	6.13	7.17	9.00	11.83	17.26	23.13	34.06	45.15	55.47	82.08	107.87
Energy at... 4000 hours operation per year. Lamps bought on $150 contract.	1 cent	3.04	3.64	4.04	4.61	6.31	8.68	12.54	16.83	24.48	32.29	37.64	53.92	67.29
	1½ cents	3.54	4.44	5.04	5.81	7.81	10.68	15.54	20.83	30.48	40.29	47.64	68.92	87.29
	2 cents	4.04	5.24	6.04	7.01	9.31	12.68	18.54	24.83	36.48	48.29	57.64	83.92	107.29
	3 cents	5.04	6.84	8.04	9.41	12.31	16.68	24.54	32.83	48.48	64.29	77.64	113.92	147.29
	4 cents	6.04	8.44	10.04	11.81	15.31	20.68	30.54	40.83	60.48	80.29	97.64	143.92	187.29
Energy at... 4000 hours operation per year. Lamps bought on $1200 contract.	1 cent	2.90	3.50	3.90	4.45	6.03	8.24	11.88	15.95	23.18	30.57	35.76	51.32	64.29
	1½ cents	3.40	4.30	4.90	5.65	7.53	10.24	14.88	19.95	29.18	38.57	45.76	66.32	84.29
	2 cents	3.90	5.10	5.90	6.85	9.03	12.24	17.88	23.95	35.18	46.57	55.76	81.32	104.29
	3 cents	4.90	6.70	7.90	9.25	12.03	16.24	23.88	31.95	47.18	62.57	75.76	111.32	144.29
	4 cents	5.90	8.30	9.90	11.65	15.03	20.24	29.88	39.95	59.18	78.57	95.76	141.32	184.29

From Table XLIII we obtain the following:

Fixed charges	$ 2.03
Maintenance 4.000 × $5.475	21.90
Energy 4.000 × 2 × $10	80.00
Total cost per unit	$ 103.93
Total cost for system	2286.46

In Table XLIII are included annual operating costs which have been calculated for a number of cases frequently met in practice.

PROBLEMS ON FUNDAMENTAL PRINCIPLES OF ILLUMINATION

1. Determine the total number of lumens per outlet required to light a rectangular woodworking room to an intensity of 4 foot-candles. The dimensions of the room are 100 ft. by 60 ft., ceiling height 20 ft. Assume a depreciation factor of 1.25 and 18 outlets. Show how to arrive at the coefficients of utilization if the standard R L M dome with clear lamp is used. Lamps are to be mounted 15 ft. above the plane of work, which is 3.5 ft. above the floor. Ceiling and walls are of medium color. State proper type and size of lamp to install.

2. Design a lighting system for a foundry 60 ft. by 200 ft.; bottom of roof trusses 28 ft. above the floor and 20 ft. apart; height to top of crane, 24 ft. Locate the units and show all calculations. Give reasons for choice of reflectors.

3. Given the plan of a general office as follows: 60 ft. by 50 ft., with two doors on the 50 ft. side; two supporting posts, 18 in. in diameter, placed symmetrically 20 ft. apart and 25 ft. from the long wall; ceiling height, 10.5 ft., light in finish and free from beams; side walls fairly light finish. Recommend the foot-candle illumination and type of fixture, giving reasons; make a sketch showing location of outlets, indicating the spacing distance; give hanging height of unit, size of lamp required and type of bulb, and actual foot-candle illumination resulting from lamp just stated as required.

4. Will the coefficient of utilization for R L M reflectors and tungsten lamps be the same in a room 15 ft. by 15 ft. by 15 ft. as in a room 40 ft. high, 100 ft. long and 75 ft. wide? Give reasons for answer.

COLLATERAL READING

Fundamental Principles of Illumination

Allemagne, H. R. D., Histoire du Luminaire (A. Picard, Paris, 1891).

Gaster, L., and Dow, J. S., Modern Illuminants and Illuminating Engineering (MacMillan Co., New York, 1915).

Harrison, W., Electric Lighting (American Technical Society, Chicago, 1920).

Walsh, J. T., The Elementary Principles of Lighting and Photometry (E. P. Dutton & Co., New York, 1923).

Blok, A., Elementary Principles of Illumination and Artificial Lighting (Scott Greenwood & Sons, London, 1914).

Bell, L., Art of Illumination (McGraw-Hill Co., New York, 1912, 2nd edition).

Luckiesh, M., The Lighting Art, Its Practice and Possibilities (McGraw-Hill Co., New York, 1917).

Luckiesh, M., Light and Work (D. Van Nostrand Co., New York, 1924).

Pierce, R. F., Principles of Incandescent Gas Lighting, Progressive Age, 974 (1912).
Sandeman, W. J., Progress in Gas Lighting, Ill. Eng., **15,** 7 (1922).
Illuminating Glassware (Symposium), Trans. I. E. S., **6,** 854 (1911).
Hibben, S. G., The Design and Manufacture of Diffusing Glass Shades, Trans. I. E. S., **11,** 895 (1916).
Luckiesh, M., The Measurement of Transmission-Factor, J. Frank. Inst., **186,** 111 (1918).
Code of Luminaire Design, Trans. I. E. S., **17,** 703 (1922).
Report on Glare, Trans. I. E. S., **17,** 743 (1922).

CHAPTER VI

LIGHT, SHADE AND COLOR

[M. Luckiesh]

Principles

Vision. — Vision is accomplished by distinguishing differences in brightness and in color. Any scene is focused upon the retina as a miniature image in light, shade and color. Light not only illuminates objects; it models and colors them. Therefore, in a broad sense, the lighting expert must be acquainted with the details of light, color, lighting, vision and the characteristics of objects. A knowledge of these details involves physical measurements, the physiology of vision, the psychology of perception, and aesthetics. Visual acuity, the minimum perceptible brightness-difference, and differences in hue and in saturation also play a prominent part in vision. The last named are influenced very much by the spectral character of the illuminant.

Characteristics of Objects. — The appearance of an object depends upon its own characteristics as well as upon the lighting. A perfect mirror and an object having perfectly diffuse reflection show the two extremes, respectively, of specular and diffuse reflection. Similarly for transmitting media, the two extremes are represented respectively by perfectly transparent and diffusing media.

Shadows. — The measurement of intensity of illumination in terms of foot-candles is a much better means of appraising the lighting of a plane, such as a page of reading matter, than of three-dimensional objects. In general, seeing involves the recognition of three-dimensional objects and this is particularly the case in many industrial processes. Therefore, the study of shadows is of great importance in lighting.

The direction of a shadow is determined by the position of the dominant light source. The character of the edge of the shadow depends upon the solid angle subtended by the light source at the shadow-producing edge. The brightness of the shadow depends upon the amount of indirect or scattered light and upon the reflection-factor of the surface upon which the shadow is cast. The character of shadows depends upon the lighting unit and upon the so-called " system " of lighting.

The most satisfactory seeing usually occurs under conditions of a single predominant light source and some indirect light reflected from the surroundings. The sun, owing to its great distance, is a light source of small solid angle. For this reason shadows outdoors on a clear day are sharply defined. However, their harshness is relieved to some extent by the large percentage of skylight. On an average clear day the total sky contributes about 20 per cent of the total light reaching a horizontal plane at noon. Indoors the amount of indirect light — that is, the light reaching the shadows — is often considerably less than that found outdoors. One of the annoying conditions in lighting is a multiplicity of shadows of about the same degree of brightness. In most cases satisfactory seeing of three-dimensional objects demands a dominating light source.

Scale of Values. — The term " value " may be borrowed from the artist to designate the brightness component of a color. In lighting, relative brightness is as important as absolute brightness. The latter is of importance from the viewpoint of glare and of certain physiological phenomena of vision. In judging some other aspects of seeing and especially in appraising the aesthetic aspect of an interior, relative brightnesses, or values, are of primary importance. There has been no standardization of the scale of values which the artist employs, but a suggested standardization is indicated below.

Artist's Scale		Suggested Scale
Symbols	*Values*	*Reflection-factors*
B	black	0–10 per cent
LD	low dark	10–20 per cent
D	dark	20–30 per cent
HD	high dark	30–40 per cent
M	medium	40–50 per cent
LL	low light	50–60 per cent
L	light	60–70 per cent
HL	high light	70–80 per cent
W	white	80–90 per cent

The artist has used nine values, and fortunately the reflection-factors of commercial pigments and other media are such that it is possible to standardize such a scale. Black and white as actually found are merely relative terms, and some allowance must be made for this fact in using the suggested scale. It might be advantageous for the lighting expert to adopt these terms in order that he may readily describe the decorative scheme of a room.

The " blackest " pigments and other media, as ordinarily used, reflect several per cent, and the " whitest " pigments or other media, less than 90 per cent of the incident light. Thus, it is seen that the

range of contrast represented by the decorator's media is usually about one to thirty. The secondary or reflected light has limitations.

Terminology of Color. — The color names now in general use are unsatisfactory because they are unwieldy and uncertain in conveying a description. They have no scientific basis and in this respect they are almost meaningless. The data furnished by the spectrophotometer should be more widely disseminated and utilized, but further color notation is also necessary. The notation should be such as to bring to the mind an image of the color as it appears to the eye. The data yielded by the monochromatic colorimeter appears most satisfactory for this purpose. The following definitions may make the matter clearer.

Quality of luminous flux is that property of luminous flux determined by its spectral distribution. Such data are obtained by means of the spectrophotometer.

Color of luminous flux is the subjective evaluation by the eye of the quality of luminous flux. Any color can be expressed in terms of its hue, saturation and brightness, reflection-factor or "value." There is no simple relation between color and quality of luminous flux. Many colors which appear the same to the eye may differ widely in quality or spectral distribution. However, identical spectral distributions or qualities result always in the same color as appraised by the eye.

Hue is that property of color by which the various spectral regions are characteristically distinguished. All colors except purples and white may be matched in hue with spectral colors. In the case of a purple, the spectral hue which is complementary to the given hue is ordinarily used for scientific designation.

In many cases the hue is directly apparent in the name of a color; but there are a great many color names in daily use which are burdensome owing to the lack of any suggestion of hue. The hue of a color is determined by comparing the color directly with spectral colors. If a match in hue be made between a given color and a spectral hue at equal brightnesses, in general it will be found that the two colors do not yet appear alike. The difference is accounted for by the difference in saturation.

Two hues are complementary if when mixed they produce white. White may be considered as a color having no hue. By the mixture of luminous fluxes of two or more hues, properly chosen both as to hue and intensity, a resultant luminous flux may be obtained which has the color white. Whenever luminous fluxes of two or more hues are mixed, the resultant luminous flux, though it may have some dominant hue, will ordinarily be evaluated subjectively as having an admixture of white.

Saturation of a color is its degree of freedom from admixture with white. Monochromatic spectral light may be considered, for purposes of measurement, as having a saturation of 100 per cent. As white light is added, the saturation decreases, until, when the hue entirely disappears, the saturation is zero. White, therefore, is the limiting color having no hue and zero saturation.

A *tint* is produced by mixing white light with a spectral hue. That is, all unsaturated colors of a certain dominant hue are tints of the completely saturated color or spectral hue. Tints, then, are colors of partial saturation.

Brightness of a color may be expressed in terms of lamberts or in terms of relative brightness. For reflecting media the relative brightness may be expressed in terms of reflection-factor or "value."

A *shade* is produced by decreasing the brightness of a color. In the case of pigments, for example, the addition of various quantities of a perfect black results in the production of various shades of the color.

Notation of a Color. — It is not difficult to visualize the dominant hue in terms of spectral hues after a little acquaintance with the latter. The hue is specified in wave-lengths of light. It is not so easy to estimate the degree of saturation or percentage of white, but this is less important in general than hue and it can be visualized sufficiently closely for practical purposes. Relative brightness, or reflection-factor, can be visualized in terms of the value-scale discussed in a previous paragraph.

A sequence of symbols, such as $H : S : B$, may be used in describing the color of a luminous flux, where H is the hue, S is the saturation, and B is the brightness (relative or absolute). Thus a medium-gray paper illuminated by the light of a candle flame (or a colored paper of the same appearance) may be expressed as 0.593 : 87 : 45. The first number is the wave-length of the dominant hue in terms of μ; the second is the percentage of saturation; the third is the value, or reflection-factor.

Analysis of Color. — In general, the light which reaches the eye directly from primary light sources, or is reflected from objects, is colored. Colorless light — white light — is the rare exception and there is no general agreement in this respect. There are various ways of analyzing or measuring color. The most analytical method is that of the spectrophotometer, by means of which the relative amounts of radiant energy of various wave-lengths are determined. The result is the "spectrophotometric curve" which is very useful to those skilled in interpreting it. By this means, illuminants and reflecting and trans-

mitting media are analyzed as to spectral characteristics. In Fig. 116 are presented the spectrophotometric curves of various common illuminants.

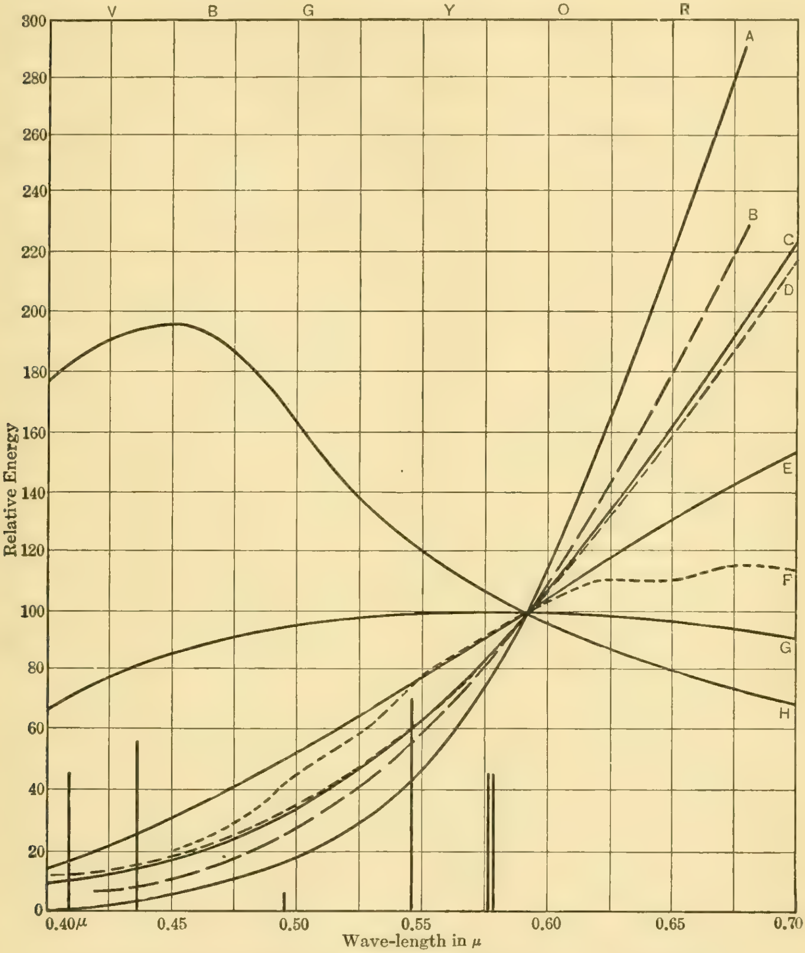


FIG. 116. Spectral Distribution of Energy in Common Illuminants.

A — Kerosene Flame.
B — Carbon Filament (3.1 w.p.m.h.c.).
C — Acetylene.
D — Tungsten Filament (7.9 lumens per watt).
E — Tungsten Filament (22 lumens per watt).
F — Incandescent Gas Mantle.
G — Sunlight.
H — Skylight.
Short Vertical Lines — Mercury Arc.

Other instruments for the measurement and analysis of color are in general synthetic; that is, they measure in terms of the appearance, or of the mixture, of certain standards. The eye is synthetic in its operation, seeing white without analyzing it into any of the vast number of hues, mixed in various proportions, which may compose it. White can be made by a great variety of mixtures of different components, such as yellow and blue; red, green and blue; purple and green; violet, blue, green, yellow, orange and red.

There are many tintometers which measure color in terms of arbitrary standards. The latter may be colored glasses, gelatine filters, solutions, etc. These are useful in the industries but are not of much value elsewhere.

The trichromatic colorimeter measures color in terms of red, green and blue. It is a well-known fact that a mixture of lights of these three primary colors in various proportions will match any color. Various sets of these primaries are possible. This is a disadvantage because the primaries cannot be easily specified. The results of this instrument may be presented in terms of the physical mixtures or in terms of sensation values. The light of a candle flame would be analyzed in sensation values approximately as red, 55 per cent; green, 40 per cent; blue, 5 per cent.

The monochromatic colorimeter is the most satisfactory colorimeter for analyzing color in terms of what the eye sees in appraising the color. By means of this instrument color is analyzed into hue, saturation and brightness. The dominant hue is compared with the spectrum and is specified in terms of wave-length. The spectrum is a ready-to-use invariable standard for this purpose. After a spectral hue is chosen which corresponds to the dominant hue of the color, the former is mixed with white light until the proper degree of saturation is reached. In this case the spectral hues are considered to be completely saturated; that is, of 100 per cent saturation. If white light comprises 40 per cent of the resulting mixture, the color is said to be of 60 per cent saturation. The brightness factor is measured by a photometric method, and is usually given as reflection-factor. Purples — for which no spectral hue is available — are usually measured by this method in terms of the complementary hue — a green. A disadvantage of this method at the present time is the lack of a standardized white light which can be readily reproduced. Clear noon sunlight appears to be a satisfactory white and it is fairly constant over various parts of the world. However, there are obvious difficulties in its use.

By this method the light of a candle flame would be indicated as having a hue corresponding to 0.593μ and a saturation of 87 per cent.

Sometimes the latter would be given as 13 per cent white. In this case the brightness factor depends upon whether the flame or an illuminated white surface is under consideration.

Graphical Representation. — The results obtained by means of the trichromatic colorimeter may be plotted in tri-linear coördinates, there being three quantities corresponding to the relative amounts of the three components, namely, red, green and blue. The geometrical figure is an equilateral triangle, each side forming a base line for the component indicated by the opposite apex. The vertical distance between the base line and the apex may be divided into a hundred equal parts, and a distance as measured from the base line to the apex represents graphically the proportion of that particular component.

By using this color triangle as a base and erecting a double pyramid, all colors may be represented, including all tints (to white at one apex) and all shades (to black at the other apex).

There are various possible ways to represent the results obtained by means of the monochromatic colorimeter but none is in use at present.

Color Mixture. — In many applications of color in lighting, the principles of color mixture may be utilized. The greatest difficulties have been encountered perhaps through the confusion of the primary colors. There are three general methods of color mixture, namely, the additive, the subtractive and the juxtapositional, which is a special form of the additive method. Many applications of color mixture involve both methods.

Matching a color in hue by a proper mixture of three primary colors, such as red, green and blue, is termed the additive method. Many sets of primary colors can be used, and a satisfactory set can be determined by experiment. In order to obtain these primary colors it is generally necessary to subtract certain colored rays from the illuminant, usually by colored screens. The latter is an example of the subtractive method and is the one employed in the mixture of pigments. It may be demonstrated by superposing colored glasses or other filters.

The subtractive primaries are commonly considered to be red, yellow and blue, but in reality they are purple, yellow and blue-green.

From the former set, purple, for example, cannot be obtained subtractively. The two methods and their relations may be expressed as follows:

$$\begin{aligned} \text{Red} + \text{Blue} &= \text{Purple},\\ \text{Green} + \text{Red} &= \text{Yellow},\\ \text{Blue} + \text{Green} &= \text{Blue-green}. \end{aligned}$$

It will be noted that the results in the foregoing addition of lights are the subtractive primaries and that the latter are complementaries of the

additive primaries. By transposing any of the quantities from the left-hand member of the equations, subtractive combinations are obtained and their results become obvious. The tendency of additive mixtures is toward white; the tendency of subtractive mixtures is toward black.

It is seen that the results of the additive method are those of true addition of light. The juxtapositional method is exemplified by staining one edge of a pack of white cards red and the opposite edge green. After alternate cards are reversed in such a manner that an edge of the pack consists of red and green narrow strips, this edge when viewed at a distance will appear yellow. That is, the results are the same, as to hue, as those obtained by means of the additive method. However, the brightness is not equal to the *sum* of the two — red and green — but is the *average* of the two. The juxtapositional method of color mixture is exemplified in textiles, in certain processes of color photography, and in lighting by means of color screens made up of juxtaposed colored filters. This method is sometimes useful in making colored screens for lighting purposes. It can be demonstrated by mixing colors by means of colored sectors on rotating disks.

Color and Vision. — The visual phenomena of color have been very extensively studied; yet there remains a vast unexplored unknown. Many of the problems pertaining to color which arise in lighting practice can be solved, or at least can be better understood, by applying present knowledge pertaining to color and vision. A few of the most important phenomena will be briefly described.

Simultaneous Contrast. — Colors mutually affect each other when viewed simultaneously, the magnitude of the influence being greatest when the colors are in juxtaposition. The phenomena may be divided into two general parts, namely, hue-contrast and brightness-contrast. As these two influences are usually at work simultaneously, it requires keen analysis to diagnose a particular case. They are important in the appearance of colored objects and must be credited with supplying a great deal of beauty to all vari-colored objects. An excellent demonstration can be made by placing a piece of white cardboard against a colored background. The former will appear of a delicate tint whose dominant hue is approximately complementary to that of the colored environment.

Growth and Decay of Color Sensation. — The various color sensations do not rise to full value immediately upon presentation of the stimuli and likewise they do not decay to zero immediately upon cessation of the stimuli. Further, the different color sensations rise and fall at different rates. Of the red, green and blue sensations, the green is the most sluggish and the blue the most active.

After-images. — After a stimulus of a color sensation is removed, the sensation persists for some time, the length of time depending upon the color. This persistence of the sensation is one type of an after-image. During its decay its appearance continually changes.

Visual Acuity. — It has been proved that visual acuity, or the ability to distinguish fine detail, is better in monochromatic light than in light of extended spectral character. The effect is not so marked for ordinary seeing; yet details, such as letters on an ordinary printed page, do appear better defined under monochromatic light. In other words, for equal discrimination or clearness of a page of type, lower intensities of illumination are required with light approaching monochromatism than with light having a more extended spectral character. Results obtained with a yellow light whose spectral character could be so altered as to approach more and more toward monochromatism indicate that the increase in defining power in this case approximately offsets the opposite effect due to the attendant decreasing illumination.

Applications. — It appears desirable from an analytical viewpoint to divide the problem of lighting into two parts, namely that which involves light and shade or distribution of brightness, and that which involves color. In dealing with the first part, one is concerned with the distribution of light; and with the second part, with the spectral character or quality of light. Sometimes these two phases are intricately interwoven but there is much advantage in general in considering them separately, especially if it be granted that lighting should be considered broadly from the viewpoint of the expression or mood of a room, the appearance of objects, satisfactory seeing, etc.

Expressiveness of Light. — The art of the decorator has been recognized for centuries but, strangely, it has not been appreciated that light in the hands of the lighting artist has greater potentiality than the decorator's media. As the decorator must depend upon reflected light, the mood or expression which he strives to obtain in a room also depends upon light. Therefore, lighting has expressive possibilities. In fact, various moods or expressions in a given room can be obtained by varying the distribution and quality of light. If light is considered as a medium similar to, but more powerful than, the pigments and other media of the decorating artist, its great potentiality will be appreciated, particularly if lighting fixtures are considered as a means to an end and if lighting effects are considered primarily. Decoration consists of lights, shades and colors. This is true of lighting effects. Architectural details, walls and ceilings, paintings and furnishings owe their visibility to light and their appearance to lighting. Their composite effects are responsible for the final expression of the interior or

exterior. That these are great truths in lighting can be determined by observation and most emphatically by experiment.

The mobility of artificial light — it comes and goes at the pressure of a switch — is a property which it does not share with the decorator's media.

Psychology of Light. — The definite data on the psychology of color are so meager that it is difficult to treat the subject briefly; therefore, only a few general statements will be incorporated here. It appears quite probable that at some future time the language of color will be generally understood.

There is general agreement in classifying colors into warm and cold groups. Spectrally these attributes are found to lie in regular succession. Yellow, orange and red are the regions to which the attribute of warmth is given. The cold colors are found at and near the blue region. The neutral colors are found in the central region, namely, the greens and adjacent colors, and neutrality is again approached at the very extremes of the spectrum. Fairly neutral colors also usually result from an additive mixture of the colors near the extreme limits of the spectrum.

In general, if the light source is visible (it may be either a primary or a secondary light source) its color plays a dominating part in the impression upon the ordinary observer. If the primary light sources are concealed, the color of the surroundings are more effective in producing the impression than the actual color of the important surface, such as a book which the observer may be reading, or goods on display in a show-window. Specific examples may make the point clear. If a semi-indirect bowl be of a warm color, such as orange-yellow, the observer whose aesthetic sense demands the warm color will often neglect to inquire further. In other words, the lighting will usually be satisfactory to him, notwithstanding the fact that the light which constitutes the predominant part of the useful illumination may be the much whiter light emitted by a gas-mantle or tungsten filament located in the semi-indirect bowl. Another example can be drawn from many installations of artificial daylight which have recently been made. Notwithstanding the fact that a quality of light closely approaching daylight is, in many cases, not only desirable, but proper, tradition or habit requires that the artificial light must be of a yellowish color. If the surroundings, such as the background in a show-window or the walls and ceiling of a picture gallery, be covered with warm colors, the white light from the artificial-daylight units can be directed upon the objects to be displayed and yet the warm appearance of the whole will be largely maintained.

A room with southern exposure, which receives much direct sunlight, can be " cooled " to some extent by the employment of cool colors in the furnishings. Conversely, a room with northern exposure can be " warmed " considerably by the employment of warm colors in the surroundings. It is true that the light is somewhat altered by selective reflection from the colored surroundings, but the major portion of the effect is often apparently purely psychological. A theatre in the summertime may be illuminated by light of the " cooler " tints.

It is well to emphasize the apparent existence of two distinct mental attitudes in regard to color in lighting. Rooms are generally decorated for daylight conditions and are presumably satisfactory when completed. However, in spite of the fact that all illuminants ordinarily used for general interior lighting are quite yellow in integral color in comparison with daylight, complaint is sometimes heard of the garish whiteness of the unaltered light emitted by modern gas and electric filament lamps. The correction resorted to is usually the application of yellow screens of glass, gelatine, or silk fabric. Why, if the daylight condition is satisfactory, is the artificial lighting too cold? Obviously the question is answered by admitting the existence of day and night criteria which are widely different. The reason for the existence of these two very different criteria possibly may be correctly attributed to tradition. Artificial light for ages was quite yellow, and only recently have the illuminants become considerably whiter. Perhaps the demand for yellow artificial light arises from some aesthetic sense which is largely due to the insistence of habit. It is difficult to account for the foregoing in any other manner, considering the tremendous difference in color still existing between most artificial illuminants and natural daylight. It is not the author's desire here to condemn this double standard but to diagnose it. It is a condition which must be met and one which involves many of the facts and applications of color science.

There are available some data on color preference, but such data must be carefully interpreted or difficulties will be encountered. In obtaining data on color preference, the observer is concerned with nothing except the colors being compared. Other considerations which enter into lighting problems call for a modification of data on color preference before the latter can be applied. For instance, pure colors are more frequently preferred than tints and shades — a fact established by various investigators; yet this does not apply to the decoration and lighting of an interior. Of the pure colors, the reds and blues are the more often preferred of a group of pigments representing the entire range of spectral colors as well as the purples. Yellow usually ranks quite low in the preference order. Strangely enough, the colors more

commonly encountered in interior decoration (cream, yellow, orange, buff, brown) generally rank low in such color-preference investigations. Perhaps, in such cases, the momentary delight in the less common color sways the judgment oppositely to the feeling resulting from prolonged association with the color. Certainly the warmer tints and shades predominate in interiors, and usually these correspond in hue to the yellow-orange region of the spectrum. The purer tints of light may be used for purely decorative purposes and may be used only when desired. This is one of the great advantages of the mobility of light.

Effect of Surroundings. — The surroundings are very important in molding the mental impression of a lighting condition. The distribution of light and shade is largely controlled by the reflection coefficients of the surroundings.

A colored surface appears colored by reflected light because it has the property of reflecting light of certain wave-lengths and of absorbing others, thereby altering the incident light. A yellow wallpaper reflects the blue rays only slightly, the result of subtracting blue rays from white light being a yellow light. A red fabric appears red under daylight because it reflects only the red rays in daylight. It appears a relatively brighter red under tungsten or gas light than under daylight for equal illuminations, owing to the relatively greater amount of red rays present in the light from the artificial illuminants per unit of light flux. Under the light from a mercury-arc lamp, the red fabric appears almost black, because there are present in the light from the mercury arc, practically no rays which the red fabric is able to reflect. This shows that the relative brightnesses of colored objects vary with the spectral character of the illuminant and that selective reflection from the surroundings is responsible for a change in the color of the incident light. Daylight entering interiors usually has been altered by reflection from many colored objects, such as buildings, foliage, pavements, lawns and earth, with the result that daylight in interiors is quite variable in quality. This variation causes difficulty in accurate color work from day to day and from season to season. As skylight is much more bluish in color than sunlight, tremendous variations in quality are apparent as the relative amounts of sunlight and skylight vary. Moreover, the variation in the relative amounts of skylight and sunlight entering windows or other openings is generally continuous.

The influence of the surroundings upon the color of the useful light at a given point, such as a desk-top, depends upon the relative amounts of light reaching the point directly and indirectly. For ordinary direct-lighting systems, the alteration due to colored surroundings is

usually appreciable although not so great as for indirect-lighting systems. In a representative case, it was found that the light from tungsten lamps in an indirect-lighting fixture was altered to a color even yellower than the old carbon lamps when the colors of the cream-tinted ceiling and brownish-yellow walls were of a very common combination. The effect is of considerable magnitude in semi-indirect installations, depending, of course, upon the relative values of the direct and indirect components.

If in a given case of indirect lighting the artificial illuminant is too cold, it is possible to obtain identical results by two expedients. In one case the walls and ceiling would be refinished with coverings of a warmer or yellower tint; in the other case, a yellowish screen would be placed over the lighting unit so as to alter the light by selective absorption.

The following sums up a few simple but pertinent facts. A yellowish surface under daylight illumination may appear exactly like a neutral surface under an ordinary yellowish artificial illuminant. Surroundings consisting chiefly of such colors as brown, buff, yellow or orange shades, which are neutral or warm in appearance under daylight, appear relatively much warmer by ordinary artificial light. In indirect and many semi-indirect systems of lighting, the alteration of the light by colored surroundings is so great as to produce in many cases an effect with a modern illuminant similar to that obtained with the old illuminants in ordinary direct fixtures.

Artificial Daylight. — For the production and appreciation of colored objects, daylight is the generally accepted standard. The arts as well as the eye have been evolved under natural light, with the result that the demand for light approaching daylight in quality for many purposes is deeply and permanently rooted. As daylight varies tremendously in spectral character, it is necessary to determine standards. Measurements of intensity and quality of north skylight on a clear day reveal a fair constancy, which doubtless accounts for the dependence upon north skylight for accurate color discrimination. However, north skylight varies from clear to cloudy days, but not so much as the light from other points of the compass in northern latitudes. Clear noon sunlight is quite constant, and although not always available represents a fair average daylight outdoors. Noon sunlight and north skylight have, therefore, been accepted as two distinct standard daylights.

There are three possible methods of producing artificial daylight; namely, (1) directly from the light source; (2) by adding complementary lights in proper proportions; (3) by altering the light from an

illuminant by means of a selective screen. The only available illuminant at present which fills directly the requirements of accurate color work is the Moore carbon dioxide tube lamp. The Moore tube emits light approximating skylight in quality closely enough for the most exacting color matching.

Some years ago the light from the tungsten lamp was combined with that from the mercury arc in such proportions as to give a subjective white light. This combination met some requirements, but could not possibly approximate daylight in spectral character owing to the discontinuous spectrum of the mercury arc. The spectrum of the light from the Moore carbon dioxide tube is discontinuous, but only for small intervals. On various occasions colored lights have been combined with the light from ordinary artificial illuminants to produce an approximate daylight effect. However, the only method of producing artificial daylight which up to the present has been extensively applied is that which involves the use of colored transmitting or reflecting screens. These have been used with gas mantles, arc lamps and tungsten filament lamps.

In cases where accurate color matching is required, efficiency should be a minor consideration and experience has proved this to be very generally true. Using modern gas-filled tungsten lamps, north skylight of satisfactory quality is reproduced by the subtractive method at losses of from 75 to 85 per cent of the original light. It has been found that colored screens can be produced inexpensively and with sufficient accuracy to meet the requirements.

Experience has shown that, for the less refined color work, little or no advantage is gained in correcting the light further than to an approximation to clear noon sunlight. For this reason practical artificial sunlight units have been developed. These units, whose important part consists of an enclosing colored-glass envelope, have been installed for general lighting purposes in many different fields. The absorption losses of these units, when used with gas-filled tungsten lamps operating in the neighborhood of 18 lumens per watt, are approximately 50 per cent. The color of the resulting light blends well with daylight entering interiors.

The quality of light known as artificial north skylight is the most generally acceptable for accurate color work, such as matching and inspecting colors. It is not used for lighting large areas in the sense of general lighting, although there are some rather extensive installations in existence.

Artificial daylight has also found its way into fields which it would not be generally expected to enter. For instance, there has always

existed a feeling of dissatisfaction with the lighting during the late afternoon, the period of the day when daylight must be reinforced by artificial light. This is perhaps partially due to a difference in the distribution of light in the two cases. However, the difficulty is also partially, if not largely, due to the difference in color.

Other Applications of Colored Light. — Many diversified applications of the principles of color mixture may be made. The stage offers the greatest possibilities, although ordinary specifications of stage lighting often provide only clear, red, and blue lamps. The range of colors resulting from mixtures of these is quite limited. As lighting effects are valuable tools in the hands of the stage director, it is suggested that facilities be provided for using at least the three primary colors, red, green, and blue, and also clear lamps. If space permits it would be desirable to add yellow lamps. Yellow can be obtained by mixing red and green, but inasmuch as it is an important stage-lighting color it is undesirable to sacrifice it in obtaining the red and green originally and then to produce it again by mixture at a greatly reduced efficiency.

The primary colors have been used in show-windows and for many special effects, such as in a certain residential installation which has red, green, and blue lamps installed above a large oval panel of opal glass set in the ceiling of a dining room. Any quality of light can be obtained with this installation, by controlling various lamps by means of three rheostats located in a cabinet in the wall. A number of installations on a larger scale have been placed in ballrooms and restaurants. Such applications should be more numerous, considering the pleasure obtainable. A few cases have been noted where colored lights have been mixed for the general illumination of theatres, billboards, special displays, ballrooms, etc. Flashers have usually been used, but rheostats can be readily designed to be mechanically operated so as to vary the intensity of the several components by imperceptible increments. Beautiful effects have been obtained by illuminating clothing models with mixtures of the primary colors, accentuating the effects occasionally by directed unaltered light. The latter effect is intensely beautified by the colored shadows which remain. These are due to a flood of colored light of a lower intensity than the clear directed light. In ordinary lighting, tints are more satisfying to the aesthetic sense than saturated colors, and these tints are readily obtained by adding lights, fairly saturated in color, to the ordinary unaltered light. In general, it is necessary to conceal the sources.

Colored light has been used successfully in the floodlighting of monuments, buildings, and pageants. In a few rare instances, colored light has been applied to billboards and other displays, and doubtless this

field will be developed eventually. Special color effects have been proposed in which complete changes are produced by properly associating the colored pigments, used in painting the scene or advertising material, with the colored illuminants. These should eventually find a wide field also on the stage and in displays. A few applications have been made, but the difficulty at present lies in the necessity of a complete grasp of color science in order to accomplish the desired results.

Colored Media. — Essential tools in applying color in lighting are colored media and a knowledge of the fundamental principles of the science of color. The latter have been briefly discussed in preceding paragraphs and a few suggestions regarding colored media are presented below. Illuminants differing in color have been harmoniously blended in many instances, but the greater possibilities of such applications naturally are found in installations of great magnitude. In the general practice of color in lighting, an acquaintance with colored media is essential. Among the chief colored media are glasses, silk fabrics, gelatines, lacquers, pigments, aniline dyes, and chemical salts. Signal glasses, with little or no correction, often afford excellent primary colors for applications of color mixture. Lacquers can be colored with aniline dyes and other materials, provided a proper solvent is employed. Often an insoluble pigment or dye can be suspended in a binding medium to a sufficient degree to enable lamps or glassware or other media to be colored by immersion.

Colored fabrics such as silk lend themselves to many applications of interior lighting. Colored solutions find uses especially in temporary lighting installations and in demonstrations.

The method of using these materials obviously varies with the problem at hand. If colored glasses of proper spectral characteristics are available they can be placed in such a position as to intercept the light emitted by the illuminant. However, if the correct tint is not at hand, it is often possible to obtain the desired result by combining colors according to the various methods of color mixture.

COLLATERAL READING

Light, Shade and Color

LUCKIESH, M., Light and Shade and Their Application (D. Van Nostrand Co., New York, 1916).

LUCKIESH, M., Color and Its Applications (D. Van Nostrand Co., New York, 1921).

LUCKIESH, M., Light and Color in Advertising and Merchandising (D. Van Nostrand Co., New York, 1923).

JORGENSEN, C. J., The Mastery of Color (Milwaukee, 1906).

DAUTHENAY, H., Repertoire de Couleurs (Société Française des Chrysanthemists, 1905).

Stocks, H. B., Colour (Scott Greenwood & Son, London, 1916).
A Color Symposium, Trans. I. E. S., **13**, 1 (1918).
Luckiesh, M., The Basis of Color Technology, J. Frank. Inst., **184**, 73 (1917).
Luckiesh, M., and Cady, F. E., Artificial Daylight, Its Production and Use, Trans. I. E. S., **9**, 839 (1914).
Martin, L. C., Colour Matching by Natural and Artificial Light, Ill. Eng., **13**, 31 (1920).

CHAPTER VII

DAYLIGHT

[M. LUCKIESH]

What Is Daylight? — The sources of daylight are primarily the sun and the sky, although an appreciable amount of the light which reaches a given point outdoors is reflected by the surroundings. The amount of direct sunlight varies inversely with the amount of skylight; that is, an increase of skylight is obtained at the expense of the amount of direct sunlight. On average clear days, when the sun is high, the amount of skylight which reaches the upper side of a horizontal surface is about 20 per cent of the total incident light. On very clear days this decreases to about 10 per cent and at very high altitudes to only a few per cent. On uniformly overcast days, obviously the light which reaches the earth comes entirely from the sky. The amount of skylight increases with decreasing zenith distance of the sun and with increasing cloudiness. The maximum percentage of skylight occurs when there is a uniform cloud-sheet corresponding to stratocumulus clouds of moderate density. The percentage of skylight then decreases, reaching its lowest values for very clear and for very cloudy skies, the latter, of course, being dense layers of nimbus. The intensity of direct sunlight decreases with the altitude of the sun, owing to the increasing depths of the atmosphere through which the direct light must penetrate. The light is diminished by absorption and by scattering due to the atmosphere. The percentage of skylight reaching a horizontal surface is easily found by comparing the brightness of a small shadow with that of the surface receiving both sunlight and skylight. All daylight quantities are extremely variable, owing to the variations in cloud-formations and in cloudiness.

Intensity. — The illumination produced by sunlight varies with the altitude of the sun, but on clear days at noon it reaches 10,000 foot-candles on a horizontal plane. The illumination due to skylight on clear and hazy days varies usually between 1000 and 2000 foot-candles. It sometimes reaches 2500 foot-candles. Obviously, the minimum intensities of skylight and of sunlight are zero. The average intensity of daylight in the latitudes of the northern part of the United States is at least several times greater in June than in December. Smoke

in the atmosphere greatly reduces the intensity of daylight. In industrial districts the intensity falls to only a small fraction of that found in the country on the same day. On clear days the absorption of the atmosphere may be more than 25 per cent.

Quality. — The spectral character of sunlight when the sun is high on clear days is fairly constant and may be considered white light. The spectral distributions of noon sunlight and of north skylight are shown in Fig. 116 (Chapter VI). Average daylight is obviously a mixture of these, the addition of skylight tending to make the total daylight bluish as compared with noon sunlight. The selective absorption of the atmosphere tends to modify the sunlight, as the sun passes from the zenith to the horizon, toward yellow and even red. Average daylight throughout the day is an uncertain quantity. It may safely be considered to be yellower than noon sunlight. The sky is blue because of the selective scattering and absorption by the atmosphere. If the atmosphere did not exist and if the region above the earth were a perfect void, the sky would be black in the daytime.

A demonstration of the selective absorption and scattering of light by fine particles can be made by means of a puff of smoke. When viewed by reflected light it is bluish; this is particularly true of the smoke curling upward from the lighted end of a cigar. The shadow of the smoke as viewed upon a white surface appears brownish in color. This shows that the smoke transmits the hues of longer wavelengths with greater facility than those of shorter wave-lengths, such as blue. Incidentally, the smoke from the moist end of a cigar, or that expelled after having been held in the mouth for some time, appears quite white. This may be accounted for by the condensation of moisture about the fine particles of smoke (small nuclei facilitate condensation), with the result that the particles are now too large to scatter light selectively. The blue of the sky is due to this selective scattering, perhaps even by molecules of the gases present. From the duration of twilight, it may be computed that there is appreciable matter in the air at altitudes of 50 to 100 miles.

Standard Daylight. — Noon sunlight on a clear day is sufficiently constant in quality or spectral character to be taken as a standard of white light. The light from a clear north sky in the northern hemisphere is also fairly constant in spectral character. These are considerations which have influenced the development of artificial daylight. The daylight which enters interiors is modified more or less by reflection from colored objects, such as trees and buildings. Owing to this modification and the variability in intensity and quality of daylight due to atmospheric conditions, clouds, the changing altitude of the

sun, and to other factors, an artificial daylight is advantageous for accurate discrimination of color.

Brightness. — The range of brightness outdoors is very great. The brightness of the sun is about 500,000 lamberts; the zenith sky at midday varies usually from 0.5 to 2 lamberts; sunlit clouds are several times brighter than the adjacent blue sky. The brightnesses of shadows on the earth are very small fractions of the preceding values. In fact the range of contrast in a landscape is represented by many thousands, exclusive of the sun. By including the sun, the range in contrast is represented by millions.

The mean reflection factors of the various earth areas as determined by viewing vertically downward are approximately as follows:

	Per cent
Woods	4
Barren ground	13
Fields	7
Inland water	7
Deep ocean water	3.5
Dense clouds	78

Nature's Lighting. — Many lessons pertaining to lighting may be gained by study and observation of nature's lighting. The ever-changing effects of light, shade and color in a landscape are of fascinating interest, producing an endless series of lighting results. The same scene changes enormously during a given cloudless day. In general, it is least interesting at noon when shadows are shortest and harshest. But as the sun sinks toward the horizon, shadows lengthen and soften and the scene may become much more attractive. The same scene not only varies from day to day but from season to season, demonstrating continually the powers of lighting.

Nature not only provides a vast variety of lightings, which may be studied profitably, but it has been a powerful influence in the evolution of taste. The general decorative scheme of interiors, with their increasing brightness from floor to ceiling, bears a resemblance to the general distribution of values in nature's landscape. The influence of lighting upon the mood or expression of a landscape is positively demonstrated outdoors. Furthermore, nature's lighting is powerful enough to influence the mood of beings, for who has not been influenced by sunny and by overcast days? Here one has an illustration of the psychology of light.

The intensity of light reaching the earth from the full moon is very small, the illumination on a horizontal plane being only a few hundredths of a foot-candle. The spectral character of moonlight is ap-

proximately the same as that of noon sunlight. This is interesting in view of the fact that it is usually represented as bluish or blue-green. It appears bluish by contrast with artificial light.

Effects of Quality. — Daylight fades many delicate colors, and a skylight glass which did not transmit any ultra-violet radiation might find applications in museums. Visible radiation, especially when accompanied by appreciable energy which is converted into heat, fades colors, but the ultra-violet rays are generally more severe in this respect per unit energy than visible rays.

A skylight glass which transmitted only the visible radiation would be advantageous in some cases, as it would reduce the temperature indoors owing to the absorption of the infra-red rays. However, this is not very promising, because from an energy viewpoint most of the sun's energy reaching the earth is of the wave-lengths corresponding to the visible spectrum. The maximum of the spectral distribution of the sun's radiation outside of the earth's atmosphere is in the visible region of the spectrum. Furthermore, the atmosphere, particularly the water vapor, absorbs the infra-red radiation very strongly.

Clear glass is opaque to infra-red energy of the longer wave-lengths. The sun's radiation entering a space enclosed by glass is partially transformed into chemical energy in the case of growing plants and partially absorbed by objects and transformed into heat. These objects are warmed and are now radiators of energy, but of such temperatures that the radiation which they emit is of very long wave-lengths. This energy cannot escape through the glass and is, therefore, absorbed and partially reradiated inward again. Thus, there is a building up of temperature until equilibrium is established, the temperature finally attained being somewhat higher than the temperature outdoors, owing to the absence of cooling breezes, etc. This explains the so-called " hothouse effect."

Pigments and other materials absorb and reflect light in different degrees. A box painted black will become hotter in the sunlight than one painted white. Similar pieces of metal, differing in color, will sink at different rates into the snow under the influence of solar radiation. Even white pigments differ in their ability to absorb and reflect daylight. Thus the covering for certain buildings is of importance. In the tropics white is the logical color for exteriors of buildings and for clothes, from the viewpoint of the coolness of the occupants.

Daylighting of Buildings. — The walls of light-courts for buildings should possess high reflection-factors if they are to be maximally efficient. Walls of buildings should be of a light color in order to conserve daylight in congested districts. Glazed terra-cotta is excellent from the standpoint of keeping clean.

In the design of buildings, the area of windows necessary for the admission of adequate daylight depends upon the latitude, the exposure, the amount of sky subtended at the windows, atmospheric conditions, etc. That it is inadequate most of the time on the lower floors of large buildings in downtown districts is evident from the use of artificial light. The areas of skylights, whether vertical or horizontal, and the daylighting results can be computed for any given conditions. However, various assumptions must be made and these should be based upon authentic data or experience.

The "saw-tooth" roof has been used successfully in many factory buildings, but where land is valuable such buildings possess several stories. Under these conditions adequate artificial light should be available, and it must be used during a considerable portion of the day in many factories. Where the direction of the entering daylight is satisfactory, and machines and various industrial operations are oriented in respect to it, it is advantageous to arrange the artificial lighting units so that the dominant direction is similar. Furthermore, in many cases where artificial light must be used more or less to reinforce the daylight, it is advantageous to minimize the color difference by using artificial daylight.

There are various means of controlling daylight in interiors. Window shades may be opaque or translucent as best suits the particular case. They may be hung from spring rollers as is commonly done. In this case there are some advantages in using two shades, the rollers being placed at about the middle of the window, one shade being pulled up and the other down. In other cases, single shades may be satisfactory, but whether they are fastened at the top or the bottom of the window is a matter of judgment in the particular case. Some shades are in use which are fastened to a large frame of the size of the window. These frames are hinged on one vertical edge of the window casing.

Shutters and louvers of opaque or of translucent material have their uses, and there are now in use some elaborate systems of louvers for controlling the light entering skylights. In some buildings where overhead skylights are used, large stationary or movable louvers can be utilized for controlling the distribution of light within certain limits. The design of these depends upon the particular conditions, but no insurmountable difficulties will be encountered by those familiar with the principles of light control.

Glasses. — There is an extensive variety of glasses available, such as clear, prismatic, sandblasted, etched, ribbed, rough-transparent and translucent. Their effects depend not only upon their own physical characteristics but upon those of the light source as well.

The transmission-factor of glasses of this character varies with the direction of light through the specimen and with the distribution of the incident light. For crystal glasses, the loss of light is chiefly due to reflection from the surfaces. Sandblasted and acid-etched clear glasses may be considered to be miniatures of the pebbled glasses. In the following table, certain results are given for crystal glasses having various kinds of surfaces. One surface of each specimen is smooth. Four transmission-factors are given for each specimen, as follows: (1) for a pencil of light with the smooth surface toward the light source; (2) for a pencil of light with the rough surface toward the light source; (3) for perfectly diffused light (light source subtending a hemispherical angle) with the smooth surface toward the light source; (4) same as (3) but with the glass reversed.

TABLE XLIV

Transmission-factors for Crystal Glasses

Specimen	Side Toward Light Source	Transmission-factors		Diffuse / irect
		For Pencil of Light	For Hemispherical Illumination	
		Per Cent	Per Cent	Per Cent
1	Sandblasted	78.3	70.2	89.7
1	Smooth	73.9	69.5	94.0
2	Acid-etched	79.4	70.9	89.3
2	Smooth	75.8	70.4	92.9
3	Pebbled	84.6	74.6	88.2
3	Smooth	79.0	74.6	94.4
4	Coarse ribs	76.6	61.7	80.5
4	Smooth	51.5	61.6	119.6
5	Fine ribs	85.8	79.3	92.4
5	Smooth	79.0	79.1	100.1
6	Wavy ribs	88.4	82.2	92.9
6	Smooth	86.0	82.1	95.5

The data in the preceding table are of interest in artificial as well as natural lighting. The difference in the two values of transmission-factor for opposite directions of the passage of the light through the specimen is important. The light lost by reflection is greatest when the rays emerge from the rough side of the specimen. This is explained by considering the principle of total reflection in the interior of a glass

prism. The glass-air surface reflects more light, in general, than the air-glass surface. That is, the reflection is greater when light passes from a medium of higher refractive index to one of lower refractive index than *vice versa.* In fact, it becomes total reflection for the larger angles of incidence in the former case.

The use of glasses of the refractive type is growing. Prism glasses are valuable for directing light into remote regions of rooms. Canopies of such glasses have been used outside of windows, in skylights of various kinds, in artificial lighting units, and in various places encountered by the lighting expert.

The transmission factor of smooth, clear glass is about 92 per cent for perpendicularly incident light, the loss of light being that reflected by the two surfaces. The amount reflected by a smooth surface varies with the refractive index and with the angle of incidence. For ordinary, clear, plane glass it varies as indicated in the accompanying table for a single surface when the refractive index is 1.55:

TABLE XLV

Angle of Incidence *Degrees*	Reflection-factor *Per Cent*
0	4.65
10	4.66
20	4.68
30	4.82
40	5.26
50	6.50
60	9.73
70	18.00
80	39.54
85	61.77
90	100.00

The foregoing table indicates the importance of the angle of incidence of light, and the problem is met in the case of show-windows, skylights, etc. Glasses vary considerably in refractive index, but the one given above represents the average commercial glass used for general purposes.

Distribution Indoors. — In the more common case of vertical skylights — windows — the distribution of daylight indoors is widely different from that of artificial light. In general, artificial light possesses a decided advantage over daylight from this viewpoint of distribution. Considerable annoyance is encountered from mixtures of natural and artificial light, owing to the difference in distribution and quality. The intensity of daylight varies enormously in most interiors lighted by means of windows, and many interiors of considerable extent cannot be lighted in the best manner by means of natural light.

Windows are sometimes sources of glare, which cannot be so easily avoided by the eyes as artificial light sources. The latter can be screened from the eyes or hung outside the ordinary field of vision. Daylight varies in quality indoors, owing to many factors such as selective reflection from objects outdoors and indoors, varying mixtures of skylight and sunlight, and seasonal variation. Artificial light is constant in quality and can be controlled in quantity.

Computations. — Computations of daylight are usually based upon the area of skylight visible at any given point. They are based upon the same principles as those for artificial light. The brightness of the light source times the area of the light source gives the luminous intensity. The inverse square law may then be called upon, provided the distance to the source is several times greater than the maximum dimension of the source. The area of the light source is usually that of the area of the opening through which sky is visible. Allowances must be made for variations in sky brightness, unclean skylights, etc.

Many arrangements of skylights are possible. Windows may be low or high, such as the clerestory windows. All these variations are potential means of improving the utilization of daylight and call for the close coöperation of the architect and the lighting expert.

Cost of Daylight. — In the consideration of natural and artificial lighting in interiors, it is often stated that natural light has one great advantage over artificial light in that it costs nothing. However, this conclusion is far from correct. In fact, it can be shown in many instances that natural light costs more than artificial light in interiors. Windows and skylights in general cost considerably more to construct than ordinary walls and ceilings of the same area. The interest in this excess in investment must be charged to natural lighting in interiors.

Overhead skylights and windows must be maintained and cleaned. The breakage in some skylights, owing to snow and ice, changes in temperature, and accident, are appreciable items. In fact, these are excessive in some cases. The cleaning of windows and overhead skylights is a large item in buildings. Even in a residence the cost of cleaning windows equals a large fraction of the cost of artificial light. These expenditures must be charged to natural lighting.

In buildings where large glass areas are installed, such as the overhead skylights in an art museum, an extra allowance for heating is made. This must be charged to natural lighting.

The light-courts in large buildings in congested cities are installed at the sacrifice of large floor areas and thus reduce the rentable space considerably. The cost of natural light in such cases is enormous. Furthermore, where land values are high, as they are in the business

districts of cities, additional investments of no small amounts must be charged to natural lighting. It may be said that ventilation is also obtained by means of windows and light courts. This is true, but ventilation is best achieved by special systems and at best only a small fraction of the areas of light-courts and of windows is necessary for this purpose.

It may be said that, psychologically, light-courts and windows will always be demanded. This might be agreed to if it were not for the fact that artificial light is often required throughout the entire day to reinforce the feeble daylight entering the windows of many offices and hotel rooms. Furthermore, millions of persons are working quite contentedly under artificial light throughout the day. If artificial lighting is of the best, it is much superior to natural lighting in many of the cases where the latter is very costly. By no means is it recommended that natural light be eliminated from buildings in general. The foregoing discussion is presented for the purpose of showing that it costs something to bring it indoors in all interiors and that it is very costly in many cases. However, it is suggested for the benefit of the lighting engineer that serious consideration be given to eliminating it in those special cases where it is obviously very costly and still unsatisfactory.

COLLATERAL READING

Daylight

Atkinson, W., The Orientation of Buildings or Planning for Sunlight (John Wiley & Sons, New York, 1912).

Luckiesh, M., A Study of Natural and Artificial Light Distribution in Interiors, Trans. I. E. S., **7,** 388 (1912).

Luckiesh, M., and Holladay, L. L., The Cost of Daylight, Trans. I. E. S., **18,** 119 (1923).

Kimball, H. H., Daylight Illumination and the Intensity and Duration of Twilight, Trans. I. E. S., **11,** 399 (1916).

Kimball, H. H., Variation in the Total and Luminous Solar Radiation in the United States, U. S. Monthly Weather Rev., 769 (Nov., 1919).

Marks, L. B., and Woodwell, J. E., Planning for Daylight and Sunlight in Buildings, Trans. I. E. S., **9,** 643 (1914).

Waldram, P. J., Some Problems in Daylight Illumination, Ill. Eng., **7,** 15 (1914).

CHAPTER VIII

RESIDENCE LIGHTING

[M. Luckiesh]

It has been stated that the home is the theatre of life, and its lighting can be made sufficiently flexible to be adaptable to its various activities, moods and occasions. The lighting in certain rooms may be theatrical, but this does not mean spectacular. It should be expressive, and its psychological influences should be drawn upon and utilized appropriately.

In the discussions which follow, fixtures are not discussed from an artistic viewpoint. Period designs are determined by the furnishings, the decorative scheme and the architecture, and the artistic features of fixtures are purely matters of taste. Fixtures should shield the light source from the eye, and the diffusing media, whether of glass or textile, should be dense enough to eliminate glare. A fixture cannot be beautiful or a lighting effect cannot be artistic if it annoys the eye. The householder and all with whom he comes in contact in the lighting of his house must appreciate that fixtures are a means to an end — a lighting effect — if the possibilities of lighting are to be enjoyed.

Light is a medium superior to the decorator's media in producing certain results. It is mobile, but its mobility cannot be utilized without adequate outlets and controls supplemented by fixtures which possess definite aims. The most desirable fixtures in some places are those from which two or more different lighting effects are obtainable. With equipment of this character, the householder will find in lighting one of the most fruitful sources of interest and pleasure. If the cost of lighting is examined critically and compared with the cost of ornaments, draperies, wall-coverings, etc., it will be found insignificant. Considering its low cost and its great potentiality, it may be said to be the least expensive of the various factors which contribute toward making a house a home.

Living Room. — The activities in a living room vary from those quiet occasions when a restful mood is desired to those when a joyous company is gathered. A flood of light is not best for these two extremes. To provide only the monotonous lighting which is the result of simple ceiling fixtures and generally inadequate equipment is to limit the

possibilities of lighting and to insure dissatisfaction. It should be the aim in designing the wiring and in selecting the fixtures to obtain a variety of lighting effects in order that lighting may do its share toward providing the proper environment. After a house is decorated and furnished, lighting is the only element having sufficient mobility to provide extensive variety in the appearance of the interiors.

Most living rooms contain a central ceiling fixture, and in the case of larger rooms, two or more ceiling fixtures are often used, but such a means of lighting this type of room may be shown to possess serious disadvantages. In the first place, a fixture in the center of the ceiling is generally in the field of view when persons are engaged in conversation in living rooms of small and moderate size. It is practically impossible to avoid glare and consequent discomfort. Even though the lamps are well shaded, there is usually a noticeable glare. In fact, the brightness of the ceiling, due to semi-indirect or totally indirect lighting, may be annoying when it must be endured for a long time. Another disadvantage of such lighting in the living room is the inartistic symmetry of the lighting effect. A simple experiment which brings out the comparison between a symmetrical and an asymmetrical distribution of light emphasizes the general desirability of the latter in rooms where artistic effects and expressiveness are obtained without a keynote of symmetry in such factors as the arrangement of furniture. This is the condition that exists in the usual living room.

In small living rooms the central ceiling fixture may be a necessary compromise, owing to the limited space. In larger rooms the ceiling fixture is usually an obtrusive object and it often apparently reduces the size of the room. As living rooms increase in size, the difficulties in lighting diminish. Portable lamps afford the most generally effective means for lighting this type of room. They are mobile; as many may be lighted as necessary; the number of lighting effects obtainable increases with the number of lamps and circuits; and the lamps may be at all times decorative furnishings. An adequate supply of baseboard receptacles makes it easy for the housewife to rearrange the furniture without being restrained by lighting considerations. This is always a desirable feature, but in most homes at present the supply of receptacles is very inadequate.

A small living room should have at least four baseboard outlets, and a room 14 feet by 24 feet should have at least six. It may be helpful to follow a definite rule evolved from analyses and experience. One such rule which meets the requirements is one baseboard outlet for each 50 square feet of floor area in the living room. Floor plugs are usually unnecessary and inconvenient from the standpoint of floor coverings;

however, there are some conditions which appear to demand them. If it is certain that a library table is to be placed permanently away from the wall, a floor plug may be provided at the proper location. It is sometimes desirable to carry the wire down through a leg of the table.

Owing to their position, wall brackets are sources of discomfort if they are not heavily shaded. They are nearly always in the field of vision when several persons are engaged in conversation in the living room. If they are depended upon for general lighting, the bright walls and ceiling are often annoying. If they are located properly and are equipped with pendent shades, they may serve as reading-lamps, but, being fastened to the wall, they do not possess the advantage of mobility which is a feature of portable lamps. Their positions may be predetermined in a manner similar to those of baseboard outlets, namely, by relating them to the arrangement of the furniture. The wiring of a new house cannot be laid out to best advantage unless the arrangement of the important articles of furniture is first considered. Wall brackets may serve purely utilitarian purposes, but their chief right to exist in the living room is as vital sparks of ornament. This is a sufficient reason for the existence of any fixture which is intended only to be decorative. A beautiful bracket equipped with a dense shade containing a small lamp is as ornamental as any piece of bric-a-brac can be. Small lamps and the largest shades compatible with artistic appearance conspire to reduce the brightness of wall brackets and bring it within proper limits for comfort. Dense diffusing glass appropriately tinted, parchment, and dense textiles are satisfactory materials for shades for wall brackets.

In the living room, and, in fact, in most rooms, the illuminants of warm tints are generally desired by those who are sensitive to the aesthetic features of their environment. This warm tone may be obtained to some extent by means of tinted shades but is more easily obtained by a tinted lamp. However, it is a common mistake to use amber instead of warm yellow. Experiments with incandescent filament lamps tinted to match the color of the candle flame emphasize the charm of tinted light in the home. Color is demanded in every aspect of the home where artistic considerations are present and it is bound to be more and more utilized in lighting.

Dining Room. — By comparison with the living room, the dining room in some respects represents the other extreme. The arrangement of furniture in the dining room is very definite, and the setting in this respect is never changed. Here, symmetry is a dominant note. The dining table is in the center of the room, and the technical

problems involved in the lighting may be solved in a straightforward manner.

In discussing the lighting of the dining room, it appears best to analyze the various methods which have been employed, pointing out their defects and desirable features. It is noteworthy that the decorator often employs wall brackets in elaborate dining rooms. They may be artistic objects, but despite their beauty, they are inappropriate for providing the important lighting of a dining table. They have little reason to exist at all in such a room from the standpoint of lighting. Even though the table is lighted by local lamps in the form of candlesticks, the lighted brackets are usually distracting and often glaring. The attention of the diners is sure to wander to them, and that feeling of unity so essential to an harmonious effect is lacking. There is a strife between the center of interest and these "side-shows." Little may be said in favor of wall brackets as ordinarily used in a dining room even as secondary fixtures, and there is much evidence upon which they may be condemned. If they are heavily shaded, equipped with very small lamps, and merely flank certain articles of furniture, they may be delightful notes in the setting.

Well-shaded candlesticks containing small lamps may be attractive on the table, and they may be very effective. They must be short in order that the view of the diners may not be obstructed, but too often they are a source of glare. Their best office is to supplement a low intensity of general lighting from fixtures which alone do not provide a satisfactory effect. If their disadvantages are overcome, they add a charm to the setting, but the unsightly annoying wire which often dangles from the central fixture prevents them from being wholly satisfactory. Candlesticks on the buffet provide a delightful touch, but too often these are so bright that they overbalance the primary lighting effect. Miniature lamps are satisfactory for this purpose, and the low voltage may be obtained from a small transformer. A satisfactory expedient is to connect two lamps of ordinary voltage in series. A further refinement in this case is a series-parallel switch, for there still may be occasions when the higher intensity of a parallel connection is desired at the buffet.

There are several types of fixtures which illuminate the dining table predominantly, but often certain details are neglected with the result that the best effect is not obtained. The shape and height of shades are usually very important factors.

The candelabrum, a cluster of hybrid candles surmounted by frosted lamps, is a ceiling fixture which has been widely installed in dining rooms in recent years. When candelabra are not equipped with shades, the

dominant light is distributed upon the ceiling. The lighting effect is not very different from that of the inverted bowl and is far from the best. If the lamps are equipped with suitable shades much of the light may be directed downward. Although the use of shades improves the candelabrum, it is not wholly satisfactory, for the diner on looking up sees these lamps or the bright inner linings of the shades. The consciousness of their presence is distracting. This and many other experiments indicate that dining room fixtures should not be hung high unless they are very specially designed to confine the downward component to the table. A candelabrum hung low and equipped with dense deep shades can be quite satisfactory, but it must be much lower than it is ordinarily hung.

The inverted bowl may be criticized for lighting the upper part of the room predominantly. It may be used to provide a low intensity of general lighting of different tints, if the dining table is supplied with small lamps. In fact, the latter is a common way out for householders who come to realize that dining under the general lighting from the inverted bowl which is already installed is quite unsatisfactory. There are thousands of semi-indirect bowls in use in dining rooms, but they were sold as ornaments and not for the lighting effects which they produce. Semi-indirect and indirect fixtures have contributed much to the development of lighting. They have shielded the eyes from the constantly increasing brightness of modern light sources, but they are out of place in the dining room except for providing secondary general lighting of a low intensity.

The shower, consisting of a group of pendent shades, is one of the most satisfactory fixtures among those which have been widely installed for lighting the dining table, provided the shades are of proper shape and are hung low enough. Generally, the shades should not be more than 3 feet above the table, their lower aperture should be small, and they should be dense and deep. Bowl-frosted lamps are usually more satisfactory than clear ones. The downward light from these dense shades is much more powerful than the diffused light and, therefore, the table is dominantly illuminated. If the shades are of a warm tint, the effect may be quite delightful. However, a shower which is satisfactory when hung low is usually very unsatisfactory when too high. The aim in lighting the dining table should be to keep the distribution of direct light confined considerably below a point about 12 or 14 inches vertically above the edge of the table.

The old type of dome, if properly designed and hung, provided a much better effect than most of the fixtures which superseded it. Its chief faults were its obtrusiveness and its wide aperture, which made it

necessary to suspend it very low. If it was raised higher, the lamps became visible and glare was the result. This has been a common misuse of this type of fixture. But instead of correcting these defects or of including its desirable effect in new fixtures, the lighting principle of the dome was abandoned when more modern fixtures were adopted. Fixture manufacturers have not realized that fixtures as objects may go out of style but fundamental lighting principles do not. This is an axiom which should be memorized by the fixture designer, the architect, the decorator and the householder. When the proper lighting effects are determined for a definite setting like the dining table, they should be retained and improved upon in new fixtures instead of being sacrificed.

The most useful fixture for the dining table will contain more than one circuit, although by specially designing a fixture, one circuit can be made to suffice. For example, a bowl with a hole located centrally in its under side is better than an ordinary bowl. If a light source is placed in the proper position within the bowl, a cone of direct light will emerge from the hole and illuminate the table. Light emitted upward from the bowl will provide general illumination for the room.

Many new fixtures, which possess definite aims in lighting the dining table and the remainder of the room in proper proportions, can be designed by a correlation of science and art.

The two most important rooms in the home from the standpoint of lighting have already been discussed. The general principles expounded are applicable to some extent in other rooms, although special problems are encountered as one progresses through the house.

Reception Hall. — In the reception hall, a ceiling fixture is usually most practicable, but an outlet may be provided for a portable lamp. This pendent fixture may be an elaborate lantern of silk or of colored glass panels; or, where appropriate, a colonial "lamp" may be a delightful note. A touch of color at this point is effective, but the intensity of illumination should be greater than is usually the case. In fact, reception halls are often dingy, despite the impressiveness and utility of adequate lighting at this point in the home.

Library or Den. — The library or den is quite similar to the living room during its quiet occasions. Satisfactory reading-lamps should be available, and the baseboard and wall receptacles should be laid out after due consideration of the arrangement of the furniture. Restfulness is the keynote of such a room, and too much general lighting or glaring brackets and other fixtures defeat this ideal.

Sun Room. — The sun room partakes of the characteristics of the living room but it is generally smaller. Portable lamps for reading

purposes are desirable. General lighting, when the occasion demands it, may be obtained by means of a portable lamp supplying an upward component. Owing to the nature of the room, a central fixture simulating a flower basket, or imitation flower boxes on the wall, in which lamps are concealed may be utilized for supplying the general lighting. Even an urn on a pedestal is a satisfactory place for concealing a reflector and lamps for indirect lighting.

Bedroom. — In the bedrooms the best arrangement of the furniture should be determined, in the case of new houses, before the windows are located. It then becomes easy to determine the positions of the outlets if certain principles are recognized. A wall bracket about 6 feet above the floor may be located on each side of the dresser. A distance of 5 feet between these two brackets is desirable, even though the dresser may be much less in width. The distance tends to reduce the glare, but if the shades are dense, discomfort is seldom experienced in the bedroom because the wall coverings are usually of light tints. A baseboard outlet should be provided for small dresser lamps, or for brackets if they are mounted upon the dresser. The dressing table is treated in the same manner, but inasmuch as the user is usually seated, the brackets should be lower. However, in this case it is best to provide a baseboard receptacle for dresser lamps. If besides these a small fixture is suspended from the ceiling or from a bracket above the center of the dressing table, the top of the head will be well illuminated. This combination of brackets or table lamps and a suspended fixture or overhead bracket meets all requirements at the dresser or dressing table. A baseboard outlet near the head of the bed will provide a connection for a portable lamp, which is both decorative and useful in the bedroom. The room may be wired for a central ceiling outlet, but a fixture at this point does not provide proper lighting for the important places, such as the dresser and dressing table. A central ceiling fixture, if used, should be depended upon only for general lighting of moderate intensity, except in very small rooms.

Closets. — The closets should be wired for a pendent lamp if they do not receive sufficient daylight and artificial light. This will often be welcomed, and will pay for itself many times. Switches which operate when the door opens are not generally advantageous for closets in the home. Usually a pull-chain socket is quite satisfactory.

Sewing Room. — The sewing room in a middle-class home is usually a small room which may serve as a bedroom. A central fixture is a fair compromise for a small bedroom, but for sewing an intense local illumination is desirable. If the room is definitely set aside for sewing purposes, a pendent shade hung low may serve well, but it is desirable

to provide a baseboard outlet for a portable lamp. The "daylight" lamp has been found useful for sewing purposes.

Bathroom. — The problem in the bathroom is to provide a suitable arrangement of lamps for the mirror. The solution of this problem is very simple despite the many devices which have been designed. In order that an object may be seen, it must be illuminated whether it is viewed directly or its image is viewed in the mirror. Two light sources — one on each side of the mirror — at a height of about 65 inches, serve the needs very well. If upright brackets are used, the outlets for wires should be about 5 feet above the floor. They are low enough to eliminate annoying shadows during such operations as shaving, and, one being on each side, the face is well illuminated. The light sources are well out of the direct line of vision, and no discomforting glare is experienced if small, dense, upright shades are used. In fact, pull-chain porcelain sockets containing diffusing lamps are quite satisfactory, but in this case the outlets for wires should be about 65 inches above the floor. These fixtures provide satisfactory general lighting for the bathroom. A baseboard or wall receptacle should be provided for electrical devices.

Stairways and Halls. — Stairways are best lighted by ceiling balls or bowls controlled by the usual three-way switches. Fixtures of the same character are satisfactory for halls and vestibules. Wall brackets may be used if they are more appropriate, provided their installation is warranted by the structural conditions. However, stairways should be adequately illuminated as a matter of safety, and ceiling fixtures such as balls and bowls generally cannot be excelled.

Kitchen. — The most common error in the kitchen is to suspend a combination fixture from the center of the ceiling. On account of the gas burner, this must extend considerably below the ceiling and is often inconveniently in the way. Besides, this low position of the light sources reduces their effectiveness because the worker is often annoyed by her own shadow. A combination fixture is valuable for emergencies, but it should be a wall bracket. The central fixture should be close to the ceiling, and for this purpose an enclosing unit equipped with a clear-bulb lamp or a "daylight" lamp is quite satisfactory. Wall brackets should be installed over the important places, such as the stove, the work table and the sink. If the work places in the kitchen have been laid out beforehand with the idea of saving "mileage," it is easy to locate the outlets for fixtures.

Entrance. — At entrances, it is advantageous, when appearances permit, to place the lighting fixture near the side on which the door opens and at a point not too high. This makes it possible to distinguish the features of the caller. This can be done at the rear door regardless

of appearances. An illuminated house number is an appreciated convenience whether it is illuminated by the entrance fixture or is a self-contained unit with translucent glass on which the numbers are placed.

Porch. — The best fixture for the porch is an enclosed unit such as a ceiling ball or bowl. This is often merely a ball frosted on the inside, and although sometimes satisfactory in interiors where much light is reflected by the walls and ceiling, it is much inferior to a prismatic globe which directs the light downward. Much reading is done on porches in the summer time, and a directive unit, even though it must be an open prismatic reflector, is quite desirable. Light is lost at the open sides of the porch, and the ceiling and wall of the house do not contribute much light by reflection; therefore, the control of light by means of proper reflectors or prismatic balls is desirable.

Basement. — The basement of a house is often very much neglected from the standpoint of artificial light. Usually a light source in the center of the basement near the heating plant is considered sufficient. Nevertheless, a number of outlets in the basement are very much appreciated. One at the bottom of the stairs or on the stairway assures safety in ascending and descending the stairs. A light source above one of the laundry trays is desirable. Outlets in the fuel bins, toilet and fruit closet are desirable, and indicating snap switches at the entrances of these rooms are convenient and will eventually pay for themselves by tending to show when lamps are operating needlessly in these enclosed spaces.

Miniature Lamps. — Often miniature incandescent lamps may be used in the home under conditions where ordinary lamps are not acceptable. Furthermore, low-voltage lamps may readily be installed now that small transformers are available. These lamps may be operated on the low-voltage circuit of individual bell-ringing transformers, or one of the latter may supply a number of lamps, depending upon the circumstances. Consider the actual conditions in a certain home. On the mantle are two oriental antiques which in ages past contained small candles. Ordinary lamps could not be installed because of their size, and even if they could be, the result would be unsatisfactory owing to the excessive quantity of light. The problem was easily solved by installing very small transformers (taken in this case from "night-light" units) in the hollow metal bases of the antiques. Bayonet sockets and small automobile incandescent lamps provided a very compact arrangement and the amount of light was adequate. This arrangement made it possible to connect these lamps directly to the 115-volt plug on the mantle.

A combination of switch, socket and small 115-volt candelabrum

carbon lamp was installed in a modern phonograph in the same room. The carbon lamp was used because it was smaller than any available tungsten lamp of the same voltage. The lighting for illuminating the needle of the instrument can be made much more compact by using a miniature lamp and socket connected to a small transformer in the base of the instrument. Then the latter may be connected directly to a 115-volt base plug.

In another case, in the dining room, two very small and delicate candlesticks were equipped with miniature sockets and lamps. The medium-screw sockets and lamps would be entirely too large in this case. A small transformer was concealed back of the buffet upon which the candlesticks stood. This solved the problem very satisfactorily and again the potentiality of light in modern form was drawn upon.

A similar case was found in the study, where a candlestick was serving as an ornament. However, in this case it was found best to conceal a very small transformer in a wooden base made for the purpose. The candlestick provided with the miniature lamp was placed upon this pedestal and the ornament was thus vitalized by artificial light.

In some of these cases, artificial light could not have been applied satisfactorily without resorting to small transformers and miniature lamps. Various other uses for this kind of equipment have also been found.

A house number painted upon translucent glass, illuminated from behind by means of one or two miniature lamps fed by the bell-ringing transformer, is a convenience which is appreciated by callers.

The same general scheme is applicable to a night light in the hallway or bathroom; for lighting the clock, thermometer, or other devices; for light signals of various kinds for indicating when electric devices, such as the toaster, flatiron, or even attic and basement lights, are in operation. There is much room for developing the use of miniature lamps, sockets and transformers for the home, and, of course, for other fields of lighting.

COLLATERAL READING

Residence Lighting

TAYLOR, F. H., Private House Electric Lighting (Percival Marshal & Co., London, 1907).

LUCKIESH, M., Lighting the Home (Century Co., New York, 1920).

GASTER, L., and DOW, J. S., Electric Lighting in the Home (Sir Isaac Putnam & Sons, London, 1920).

LUCKIESH, M., Portable Lamps, Their Design and Use (E. P. Dutton & Co., New York, 1924).

Luckiesh, M., An Analysis of the Field of Home Lighting, Elec. Rev. (U. S.), **76,** 429 (1920).

Luckiesh, M., Lighting the Home, Good Housekeeping (Sept.-Dec., 1923).

French, C. H., and Van Gieson, C. J., Gas and Electric Lighting in the Home, Trans. I. E. S., **11,** 1068 (1916).

Cravath, J. R., Modern Practice in Residence Lighting, Elec. Rev. & West. Elec., **69,** 403 (1916).

Morris, W. A., and Shattuck, J. D., Residence Lighting (by Gas), Proc. Intern. Gas Congress, 266, 425 (Sept., 1915).

Cassidy, G. W., Art and Science in Home Lighting, Trans. I. E. S., **10,** 55 (1915).

The Lighting of the Home, Ill. Eng., **7,** 483 (1914).

CHAPTER IX

LIGHTING OF PUBLIC BUILDINGS

[M. Luckiesh]

School Lighting

Many of the problems of lighting encountered in schools do not differ materially from those found in other interiors. However, there are many specific problems worthy of special study. In the discussions which follow, the viewpoints are those peculiar to school buildings. The aspects which they have in common with many other structures will be passed over briefly if they are touched upon at all.

There are more than twenty million school children in the United States who are devoting several hours each day to study and to the performance of other work. The child's eyes are immature in growth and in function and, therefore, are susceptible to injury and to deformation by inadequate and improper lighting. In no other field of lighting can one find greater opportunities for serving mankind. According to statistics, about 15 per cent of the total number of school children have seriously defective vision. In many cases the percentage of these defectives has been found to increase with age. This increase can be attributed largely to the manner in which the eyes are used, and in many cases improper and inadequate lighting is a contributing factor. This is an age of prevention. Satisfactory lighting and suitable instruction in the use and care of the eyes are important factors in the conservation of vision.

From hygienic and psychological viewpoints, the order of preference for exposures of rooms is east, south, west, north.

There has been no standardization of illumination intensities for various classes of visual operations; however, the tendency is toward higher intensities than those in use in the past.

The minimum and recommended intensities of illumination for schools, as adopted by the Illuminating Engineering Society in the Code on School Lighting for School Buildings, are presented in the accompanying table.

All light sources should be properly shaded to minimize glare, because glare produces eye-strain either directly or by decreasing visibility, thereby making it necessary for the eyes to be brought nearer to

TABLE XLVI

ILLUMINATION

On the Space*	Foot-candles: Minimum Required	Foot-candles: Recommended
Walks, drives and other frequented outdoor areas if used at night	0.1	0.5
Playgrounds, outdoor	0.5	2
if used at night for baseball, basketball, etc	5	10
Storage spaces, passages not used by pupils	0.25	2
Stairways, landings, corridors, aisles, main exits, elevator cars, washrooms, toilets	1	3
Boiler rooms, power plants and similar auxiliary spaces	1	3
Locker spaces	1	3
Recreation rooms, gymnasia, swimming pools	3	7
On the Work*		
Auditoriums, assembly rooms	2	3
Classrooms, study rooms, desk-tops (auditoriums or other spaces when used for class or study purposes shall meet this requirement)	5	10
Blackboards, charts, etc	3	6
Library (reading tables, catalogs, bookshelves)	5	10
Laboratories (tables, apparatus)	5	10
Manual training rooms, workshops, etc	5	10
Drafting rooms, sewing	8	15

* Where the space or work is not clearly evident, the illumination may be measured on a horizontal plane 30 inches above the floor. Such a case is an auditorium. However, where the space or work is clearly evident, such as stair steps and desk-tops, the illumination shall be measured on the plane of the steps and desk-tops respectively.

the work than they should be. The latter is one of the faults of inadequate lighting and is partly responsible for the development of nearsightedness. Lighting units should be hung high so as to be as far as possible outside the field of vision.

Light sources or lighting units should be placed so that there is an adequate and satisfactory distribution of light upon the work and so that there are no objectionable shadows and sharp contrasts in brightness.

Color and Finish of Interior

Walls should have a reflection-factor within the range from 30 per cent to 50 per cent. The preferred colors are light warm gray, light buff, dark cream, and light olive green. Ceilings and friezes (the latter in the case of high ceilings) should have a reflection-factor of at least 65 per cent. The preferred colors are white and light cream.

Desk-tops and other woodwork should have a reflection-factor not exceeding 25 per cent. There are obvious exceptions, such as boiler rooms, dark rooms, laboratories for experimenting in light, radiation and illumination; dadoes in classrooms, auditoriums, etc.

The color of the edges of treads on all stairs used as exits should be such as to show the edge of each step by contrast when viewed as in descending.

Emergency lighting should be provided at the stairways and exits, and it should be reliable in order to insure safety in the case of fire or other catastrophes. It is also advisable to have switches in stairways, corridors, basements and storerooms in order that artificial light may be readily available at any time Convenient switches increase the use of light and thereby reduce accidents.

Of course, all lighting systems should be properly maintained in order to prevent deterioration due to the accumulation of dirt, to burned-out lamps, and to other causes. Windows, overhead skylights, lighting units, ceilings and walls should be cleaned as often as necessary. Neglect of these factors is quite common. It has been found that a well-regulated system of inspection and of cleaning is desirable and that this is the best way to insure against neglect. The depreciation in intensity of lighting due to neglect may be from 10 to 40 per cent in many cases.

One of the fundamental rules for proper lighting of desks is to have the preponderance of light come from the left side. This, of course, assumes that all persons are right-handed. Owing to this fundamental principle of lighting, so-called unilateral lighting has become popular for classrooms; that is, the windows are placed only on one side of the room and the desks are arranged so that the windows are on the left of the pupils. From the viewpoint of natural lighting, unilateral lighting appears to be the most satisfactory method of lighting classrooms. This method of lighting is recommended where the width of the room does not exceed twice the height of the top of the window.

For rooms of unusual width, such as auditoriums, daylighting may be provided by means of windows on the right and left sides of the room.

Windows at the left and rear, where practicable, are preferable to those on both the left and right sides of the room in the case of intermediate-sized rooms, because of cross shadows created by lighting from opposite sides of the room. Lighting by overhead sources of natural illumination, although sometimes used for assembly rooms, auditoriums and libraries, with relatively high ceilings, has ordinarily little application in classrooms. When overhead sources of natural Illumination are

used the light should come from a north skylight or saw-tooth construction and should be oriented to exclude direct sunlight.

To secure the highest lighting values in a side-lighted room, it is recommended that the room be so designed that no work space is distant from the window more than twice the height of the top of the window from the floor.

The sky as seen through a window or skylight is a source of glare. For this reason the seating arrangements should always be such that pupils do not face the windows or skylights.

Windows

Tests of daylight in well-lighted school buildings indicate that, in general, the window-glass area should not be less than 20 per cent of the floor area. As the upper part of the window is more effective in lighting the interior than the lower part, it is recommended that the top of the glass be at no greater distance than 6 inches below the ceiling. The sills of side windows should be not less than 3 feet or more than 4 feet above the floor. No light should reach the eyes of seated pupils from below the horizontal.

Overhead skylights have been tried for the daylighting of classrooms, but at present insufficient general experience is available to pass judgment.

The lighting value of a window at any given location in the interior depends upon the brightness of the sky and upon the area visible from the given location. Certain investigations in well-lighted classrooms having a fairly unobstructed horizon indicate that, under normal conditions of daylight, satisfactory intensities of illumination are obtained at any point where a minimum vertical angle of 5 degrees of sky is visible. This assumes that the windows are of the ordinary shape and that their areas are at least 20 per cent of the floor area, thereby providing sufficient visible sky longitudinally. It is important to maintain a fairly unobstructed horizon if daylighting is to be satisfactory. In cases where this condition does not exist, that is, where there are adjacent buildings and trees, a larger window area should be provided unless artificial lighting is to be depended upon for a great part of the time.

The sky as seen through the window is a source of glare; for this reason, the seating arrangement with respect to the windows is important. It is necessary to provide window shades for controlling the daylight. Direct sunlight is desirable, but it is often necessary to exclude or to diffuse it by means of shades. The latter also may perform the function of eliminating glare from blackboards. From a considera-

tion of the requirements, it appears desirable to equip each window, especially in classrooms, with two shades whose rollers are fastened near the level of the meeting rail in the middle of the window. The shades may be raised or lowered from the middle, an arrangement which provides the maximum flexibility in the shading and diffusing of the light. The shades should be preferably of yellowish material, fairly translucent, so that a considerable portion of the light is transmitted. A more complete control can be obtained by adding another pair, installed in a manner similar to the first. These shades should be dark green in order to exclude the light almost entirely. Various other types of shades have been tried and may be useful in special cases, but the double shades just described appear to answer most requirements in schools very well.

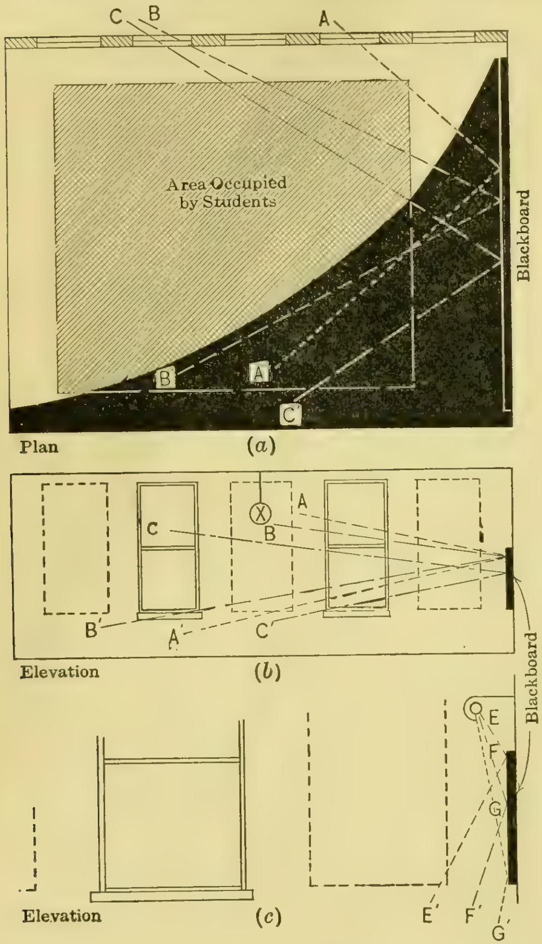


FIG. 117. Diagrammatic Illustration of Glare from Blackboards.

(a) Showing that occupants of seats in shaded area are subjected to daylight glare from blackboards.
(b) Showing angles at which glare is experienced from daylight and from artificial light.
(c) Arrangement of local artificial lighting to minimize glare.

Light reflected from exterior walls, such as those of light-courts, is very helpful in increasing the interior illumination. For this reason, the walls of courts should be painted with coatings having high reflection-factors.

It is not difficult to draw diagrams to show the possibilities of glare from windows, artificial lighting units, and from blackboards. (See Fig. 117.) These diagrams are particularly useful in studying the locations of blackboards. The latter should never be placed near or between windows. Where glare from blackboards is very annoying, it may be overcome by illuminating them by means of artificial light. The light sources in this case should be placed near and above them, in such a position that no light is directly reflected into the eyes of the pupil. A diagram in which the angle of incidence is equal to the angle of reflection will reveal the proper position for these light sources. The latter should be well shaded from the eyes of the pupils.

The artificial lighting of schoolrooms is not materially different from that of large offices and certain other interiors. If direct lighting is used, the shades should be deep and dense and the lighting units should be hung high. Semi-indirect lighting has been extensively installed in classrooms, assembly rooms, libraries, etc., and it is very successful if the glassware is dense and if it is cleaned often enough. Recently, enclosing units which emit most of the light generally downward have found favor in schools. They are efficient and require less maintenance. The lighting units in any case should be placed well outside the ordinary range of vision.

It is commonly noted that the admixture of daylight and yellowish artificial light is not satisfactory; therefore, it is sometimes better, as darkness approaches, to exclude the daylight by means of window shades and to use artificial light exclusively. Where the discrimination of color is important, as in sewing and art rooms, artificial-daylight units should be installed. Glossy surfaces of paper, blackboards, walls, woodwork, and desk-tops are likely to cause eye-strain, because of the specular reflection of images of light sources. Obviously, the best efforts toward shading light sources from the eyes and placing the lighting units out of the normal range of vision may come to naught if the pupil sits with a mirror in his hand. Glossy surfaces are near-mirrors. For this reason, in the interest of lighting and vision, matte surfaces are desirable. A great deal of good will result if children are instructed to hold their books properly and to assume a correct position with respect to the dominant light. Good lighting in schools conserves vision during the hours that pupils are subject to it. If the pupils are taught to respect and to safeguard their vision, the generation which is now growing to manhood and womanhood will not be so indifferent to those factors which are harmful to eyesight as is the present generation.

Design of a Lighting Installation

This subject is too involved to be handled in a short treatise unless limitations are set on the scope of the discussion. These considerations, therefore, will be confined to the design of a lighting installation for a classroom 32 feet by 24 feet, illustrated in Fig. 118, with a ceiling height of 12 feet, the latter having a reflection-factor of 70 per cent, and walls having a reflection-factor in the first example of 50 per cent.

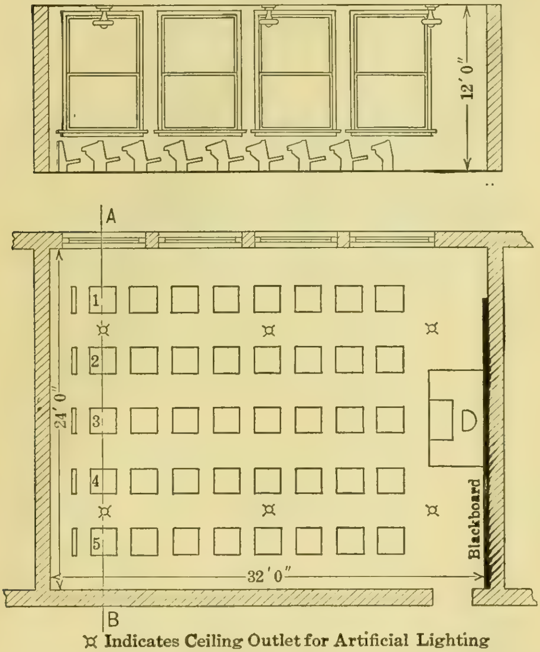


FIG. 118. Elevation and Plan of a Classroom Illustrating the Position of Outlets and Luminaires of a Direct Lighting System. In modern practice in classrooms the width varies from 20 ft. to 25 ft., the length from 28 ft. to 32 ft., and the height from 12 ft. to 14 ft.

The factors which determine the size and number of lamps to be used in a given room will be considered in the following order: first, illumination in foot-candles to be supplied; second, the floor area, which in this case is 32 by 24 feet, or 768 square feet; third, the amount of light in lumens emitted from each lamp; fourth, the coefficient of utilization of the lamps and their accessories as installed in the room.

Computations to determine the proper size of incandescent filament lamps may be made as in Chapter V or by the use of the following equation:

$$L = \frac{AI}{EN}.$$

In this equation, L is the lumens emitted by the lamp, A the area of the floor or horizontal work plane in square feet, I the illumination in foot-candles, E the coefficient of utilization, N the number of lamps required.

The first step in using this equation is the determination of the number of lamps required. From experience in school lighting it is ascertained that in order to obtain the desired distribution of illumination, luminaires should not be spaced farther apart than a distance of 1.5 times their elevation above the desk-tops. For instance, if the luminaires are hung 8 feet above the desk-tops, the maximum spacing between them should not exceed 12 feet. Now, considering the problem of a typical classroom (32 by 24 feet) having the minimum ceiling height of 12 feet, one must first determine the number of luminaires required. The plane of the work will be that of the desk-tops, which is a horizontal plane approximately 24 inches above the floor. Then if the luminaires are installed in ceiling-type fixtures and an allowance of 18 inches for depth of fixture and globe is made, the elevation of the light source above the plane of work will be approximately $8\frac{1}{2}$ feet. Hence, the maximum spacing between luminaires must not exceed 12 feet, 9 inches. With a room of these dimensions, six luminaires, therefore, would be required, spaced approximately 12 feet apart as illustrated in Fig. 118. In this example assume that an illumination of 10 foot-candles is desired. Assume also that a luminaire of highly diffusing enclosing glass is chosen and that the ceiling and walls have reflection-factors of 70 per cent and 50 per cent respectively. Under these conditions, the coefficient of utilization will be 0.39. Applying the formula

$$L = \frac{32 \times 24 \times 10}{0.39 \times 6} = 3282 \text{ lumens.}$$

How much to allow for depreciation with a given type of luminaire depends to a considerable extent on the locality and the nature of the work carried on. Experience has shown that a factor of safety of 1.3 provides for average conditions if a schedule of regular and frequent cleaning is adhered to. Applying this factor to the problem at hand, it will be necessary that each lamp supply (3282×1.3) 4267 lumens.

The 300-watt lamp is the nearest size of clear-bulb gas-filled tungsten lamp which will supply the required lumens, whereas the nearest size of daylight gas-filled tungsten lamp which will supply the required lumens is the 500-watt lamp.

In a room of this size, only four outlets are necessary if indirect-lighting luminaires or semi-indirect luminaires with dense glass bowls are used. The utilization factor for semi-indirect lighting with dense glass luminaires is 0.33 for the same room and conditions used in the previous computation. Applying the formula,

$$L = \frac{32 \times 24 \times 10}{0.33 \times 4} = 5818 \text{ lumens.}$$

Allowing for depreciation as was previously done, 5818 × 1.3, or 7563 lumens, are necessary from each of the four light sources. The nearest size of clear-bulb electric filament lamp is 500 watts. Here a total of 2000 watts would be used as compared with 1800 watts in the direct-lighting case, but the illumination intensity would be slightly greater in the former. Of course, the illumination intensity would be identical in the two cases if it were possible to obtain lamps of the exact size computed.

Auditoriums

There are some general lighting principles applicable to all auditoriums, but the details of lighting are as varied as the architecture, the decorative schemes and the purposes of such interiors. The lighting of such interiors is important enough to warrant much study of any specific case.

In all auditoriums it is assumed that there is an audience facing in a certain general direction and a person or persons located in front and facing the audience. Obviously, then, there are two viewpoints to be considered. However, if the lighting of the auditorium cannot be made satisfactory from both viewpoints, it is obvious that the audience must be given first consideration.

There should be no high brightnesses in the normal visual field and, if possible, all light sources should be well shaded from the eyes. Low general brightnesses of lighting units and walls are generally desirable and excessive contrasts should be avoided. The intensity of illumination should be sufficient to enable the audience to read with comfort. The practice of controlling the artificial lighting of the auditorium by means of dimmers is growing, and it is a very commendable one. This not only eliminates the abrupt changes in intensity which are annoying but it also provides the possibility of adjusting the light to the intensity desired for any event.

In general, a much greater intensity of illumination upon the platform, stage or chancel is required than in the auditorium. It is desirable to eliminate glare from the auditorium light sources as viewed by those on the platform, but this is sometimes difficult to do. Furthermore, in order to illuminate the platform sufficiently to satisfy the audience, it is often necessary to use concealed footlights and other concealed light sources which are glaring, especially when the auditorium is dark. These light sources can be frosted or shielded by diffusing screens, thereby lessening the annoyance of after-images. Incidentally, the background of the platform, stage or chancel should not possess a high reflection-factor. If it does, it is likely to appear

quite bright and, therefore, when the auditorium is dark or dimly lighted, it will present a high contrast to the audience.

Some quite harmless-appearing backgrounds are quite discomforting and fatiguing, even though no light sources are visible to the audience. These are excellent examples of the undesirability of high contrasts in brightness.

Exit lights are usually required by law, and the building codes should be consulted as to their number and location. Emergency lighting circuits are often required. In some public buildings these are supplied by means of storage batteries in order to insure, as much as possible, their being available when the emergency arises.

The minimum intensity permissible for auditoriums is about 1 foot-candle, although at least 3 or 4 foot-candles are usually required for reading without eye-strain. If an auditorium is lighted by means of vertical windows, they should be in the side walls, preferably on both sides. If they are recessed or set in thick walls, the possibility of glare from them is reduced. Windows at the rear are desirable, and if only one wall is available for them, the rear wall is usually the best. An audience should not be required to face windows; fortunately, this is seldom the case except in churches, where the windows are usually stained and therefore are reduced in brightness. The windows in the side walls should be higher than in ordinary rooms. The light should be controlled by means of shades, louvers, etc.

Overhead skylights of small or moderate areas may be used successfully in auditoriums, but there are inherent disadvantages in maintenance and in the exclusion of daylight when this is desired.

Inasmuch as it is difficult to illuminate the platform by means of windows at its sides or back without annoyance to the audience, it is usually desirable to provide auxiliary artificial lighting for it, even in the daytime when the auditorium is lighted by means of windows.

The possibilities of artificial lighting are much more extensive than those of daylighting. In auditoriums where the ceiling is high, the chandelier may be still used successfully, thus providing one of the excellent opportunities, which are decreasing in number relatively, for the artist in fixture design. If these chandeliers are hung very high, frosted or other diffusing lamps can be used. However, it is best to provide diffusing shades if possible.

Semi-indirect lighting units with very dense bowls have found much favor in auditoriums. They satisfy the demands for a luminous unit, and still most of the light is well diffused by reflection from the ceiling and upper walls. These are perhaps the best solution for the less pretentious interiors of this character.

When the ceilings are high and dark it is necessary to use a direct-lighting unit. This can be made in the form of a deep lantern with luminous panels and an opening in the bottom. This opening may be covered with wire-glass as a safeguard and it may be desirable to have this glass slightly diffusing. Sandblasting or acid-etching suffices if a slightly milky glass is not available.

Indirect lighting units of a variety of designs may be devised. They may appear to be lanterns; they may have slightly luminous bowls; or they may be opaque objects as decorative as desired. Silvered reflectors are usually employed in these in order that they may be of the highest efficiency obtainable in a practicable manner. Very attractive pedestals have been used in many cases, the light sources and silvered reflectors being concealed in bowls surmounting the pedestals.

In an auditorium where there are many ornamental details, lamps and reflectors may be concealed behind them. Thus cornices, rosettes, etc., conceal the lighting units, and the ornamental details are not only modeled by the distribution of light and shade but the auditorium is lighted indirectly. Direct lighting units may be concealed behind beams running across the ceiling if the ceiling is low enough and the beams are deep enough. Imitation flower boxes or more formal devices may be fastened to the walls for the purpose of obtaining indirect lighting. These are examples of the numerous devices which are available.

If there are galleries, the lighting under these must be considered in addition to that of the auditorium proper. Furthermore, the auditorium lighting should be such that it does not annoy the occupants of the galleries. In other words, the light sources in indirect units, behind coves, in wall boxes, etc., should not be visible from the galleries. One of the common annoyances of the stage boxes is the glare from the footlights.

As architects and illuminating engineers learn to appreciate a new viewpoint toward lighting — that it is a medium to be handled as the decorator employs his media — auditoriums will be painted with light. Furthermore, the mobility of light will be drawn upon to provide the element of variety. If in the indirect lighting units, in the coves, in the spaces behind cornices, several lighting circuits are installed, a variety of effects may be obtained. The light obtained from these circuits may be of different tints. In some cases the purer colors could be used and an extreme variety of tints could be obtained by mixing them. In such a case dimmers are desirable. If the various circuits are arranged in accordance with arches, cornices, panels, etc., it is obvious that many decorative schemes are available.

There are a few notable instances where light sources of various kinds and tints have been located above decorative glass ceilings, the different kinds of light sources being distributed with proper respect for the various elements in the ceiling. However, this is permissible only in the more elaborate interiors. The future appears to call for the use of a multiplicity of circuits laid out for the purpose of utilizing the mobility of lighting.

Theatres

In theatres there are again the two viewpoints or two general lighting problems, namely, that of the stage and that of the auditorium. Furthermore, at the present time, the moving picture theatre affords some special problems in lighting.

The Auditorium. — Public auditoriums having been discussed, only the problems and possibilities peculiar to the theatre will be touched upon. Here, lighting effects bordering on the spectacular are permissible. Various color effects and lighting novelties may be introduced. Dimmers for controlling the auditorium lights are desirable. They make it possible to control the light for certain lighting effects and to reduce or increase gradually the intensity of the illumination when the curtain goes up or down or when the pictures begin or cease.

Moving Picture Theatre. — In the moving picture theatre, there are a number of problems pertaining particularly to the physiological aspects of vision. A short period of discomfort is experienced as one enters a darkened theatre with eyes adapted to daylight intensities. In many cases it is possible to decrease gradually the intensity of artificial illumination from the street entrance to the auditorium entrance. In the case of a long, straight foyer leading from the street to the auditorium, this is likely to be the result of the natural gradual decrease in the intensity of daylight. Just before the pictures begin, illumination of the auditorium may be gradually decreased. Such refinements are appreciated by the audience.

Glare. — A common source of glare is the bright screen in contrast with the dark surroundings. Attempts are made to decrease this and to make the surroundings of the screen more attractive, by employing effects of colored light on the stage. This can be very successfully done. However, from the standpoint of safety and of eye comfort, it is well to provide a low intensity of illumination in the auditorium. Other common sources of glare are the lighting units used by the orchestra. This defect can be remedied to some extent by careful attention to the design and use of the units; however, in the dark auditorium, the

illuminated surface of the music is often glaring. A solution is to provide a pit for the orchestra.

Flicker. — One of the annoying features of the moving picture is the flicker. This is greatly reduced by mechanical perfection in the projecting machine; however, it is always present to some degree. The improvement of projection apparatus is still a possibility, but it will not come about unless certain psycho-physiological aspects of vision are taken into consideration. The conspicuity of flicker depends upon (1) the relative minimum and maximum brightnesses which are altered; (2) the absolute value of the maximum brightness; (3) the wave-form of the stimulus; (4) the frequency; (5) the contrast with the surroundings; (6) the amount of scattered light reaching the screen; (7) the spectral character of the stimulus (to a small extent in the practical case); and to other minor factors. Practical expedients include reducing the brightness of the screen, increasing the intensity of light in the auditorium, and increasing the amount of scattered light which reaches the screen.

The Stage. — The real art of stage lighting is the artistic expression of an individual possessing an intimate knowledge of the facts of light, shade and color.

There are many incongruities in stage settings, especially in the older, so-called realistic settings. Realistic is an unsatisfactory term, for many of the effects are far from realism. Painted perspective and painted shadows are effective in producing realism, but unfortunately the effect is spoiled for the discriminating when the real shadows do not harmonize with the painted ones. Light from the footlights produces shadows quite in discord with the painted ones and also illuminates the features of the actors in an unnatural manner. Moonlight is often represented as a flood of blue-green light, but as the villain slinks across the moonlit area, no sharp, harsh shadow accompanies him. The so-called realists may sometime discover that direct moonlight casts a single, definite shadow!

In recent years there has been a reaction, and a small number of enthusiastic artists are striving to do away with the incongruities and distractions of the realistic setting. The aim in the modern movement is to harmonize play, setting and lighting and to subordinate the material to the psychological. Details are reduced to a minimum and realism in the older sense gives way to the expressiveness of light, shade and color.

Experiments have been made with many devices, such as the sky dome instead of the borders and back drop. This dome is of translucent material and is illuminated from the rear. Plain drops have been used.

Color is employed for its deeper meanings. The lighting effects have run the whole gamut from silhouettes to brilliantly illuminated objects and actors seen against a dark background. The mobility of light has enabled it to be interwoven with the drama, with music, and with the dance. The language of color has been drawn upon and many novel effects have been tried.

Stage-lighting equipment ordinarily consists of footlights, border lights, spotlights, floodlights and various colored media. Elaborate sets of dimmers and electric circuits are interconnected by means of switches. Of course, the lighting requirements depend upon the production so that there is no permanent arrangement. On the smaller stages it is a common procedure to provide three parallel circuits containing clear, red and blue lamps, respectively. By referring to the principles of color-mixture presented elsewhere, the limited possibilities of these three circuits will be recognized. By mixing red, green and blue lights, any desired color can be obtained. If space is limited and extreme flexibility is desired, these three primary lights afford the greatest possibilities. Next would be added a circuit of clear lamps. This would afford light when a conspicuous tint was not desired. Tints could be obtained directly by adding colored light to the light from the clear lamps. Next a circuit of yellow lamps might be added, because yellow light is very commonly desired for the stage.

Color mixers, color wheels, gelatine filters, color caps, colored lacquers, and many other requisites for the stage can be purchased from the supply companies. The recent developments in incandescent filament lamps have simplified to some extent the production of lighting effects, while automatic arc lamps have also reached a high state of development. With filament lamps, spotlights, floodlights and other apparatus can be controlled at a distance with greater surety than the more intricate mechanisms of arc lamps. Where very high luminous output is required from a single source, the arc lamp leads the filament lamp. Colored lacquers are fairly satisfactory when used on the vacuum tungsten filament lamps, but in general they fade quickly on the hot bulb of the gas-filled incandescent lamps. Colored gelatines may be used in frames, and if some ingenuity is expended in ventilating the device they are satisfactory for stage lighting. Colored glasses do not fade appreciably and are best for lighting effects which are more or less permanent.

Museums

The museum is primarily a place where objects are displayed, and these objects owe much of their value to light. If they could not be seen they would not be much in demand. If they are seen to the best

advantage, in their true forms and colors, they are appreciated more than when they are poorly lighted. The problems of lighting in museums vary with the character of the exhibits and with the dimensions of the rooms. The exhibits may consist of paintings, objects in cases, sculpture, furniture, tapestries on walls, etc., or, in natural history buildings, of animal groups, insect collections, fossils, skeletons, etc. These and the many other exhibits afford an interesting variety of problems. Daylight is, in general, the best quality of light for museums, but the distribution of daylight can be controlled only to a certain degree indoors and it cannot be controlled outdoors. Artificial light can be completely controlled both in distribution and in quality. Artificial daylight is desirable where the appearance of objects is important and it is being installed in museums.

The design of satisfactory lighting in museums calls for the closest coöperation between the architect and the lighting engineer. The location of windows, the size and type of skylights, the character of the wall coverings, the architectural details, and many other elements, are more or less determined by the character of the exhibits. Northern exposure in this hemisphere is desirable for many activities, but it appears that southern exposure, or daylight consisting of a mixture of skylight and sunlight, is approved by most competent judges for art museum galleries. This assumes that the direct sunlight is diffused by curtains, glass or other media. The daylight entering from the north is often modified by draperies or by other means, in order to suit some exacting critics. In general, low windows are not very satisfactory for museum galleries, but they are better suited for small rooms containing tapestries, furniture or cases.

Galleries in which paintings are hung upon the walls are best lighted from overhead sources if the light is directed chiefly upon the walls. Windows in the side walls, unless very high, are quite unsatisfactory, for images of them are reflected from the glass or varnish, directly into the eyes of the observer. Clerestory or very high windows may be satisfactory in rooms which are not much wider than they are high. Picture galleries are commonly lighted by means of overhead skylights, but unless the light is controlled by means of louvers there is usually too much light directed downward as compared with that directed upon the lower walls where the pictures are hung. Furthermore, if the skylight is of large area and not very high, its image is reflected by the pictures. This downward component has been reduced in some cases by means of a velum, consisting of a large horizontal sheet of some satisfactory media, either opaque, highly absorbing, or slightly translucent. This is hung or supported a few feet below the skylight.

Inasmuch as it possesses an area less than that of the floor, the daylight passes by its edges and falls obliquely upon the paintings. This device is a makeshift and is usually unsightly. It is possible to incorporate the principle into the architectural design with pleasing results.

In designing the lighting for any gallery, the law of reflection of light should be applied by means of diagrams. Analyses of this character will yield valuable results as to the expanse of skylight permissible, the location of artificial lighting units, the desirable height of room as compared with the dimensions of the floor, the desirable locations of windows, etc. Thus, in picture galleries it appears satisfactory in most cases to consider a height of 10 feet above the floor as being the limit of the wall space on which pictures are to be hung. The eyes of an adult may be taken as 5 feet above the floor. Therefore, a line drawn from the eyes to a point on the wall 10 feet high, and then reflected at the same angle, will meet the ceiling at a certain point. Light from the latter point would be reflected from the top of a picture 10 feet high into the eyes of the observer at the original position. By such a series of diagrams a complete analysis may be made which will be of great fundamental value in designing the galleries and their lighting.

The wall coverings should be a fairly neutral tint in order to avoid the effects of simultaneous contrasts of colors. They should be dull in order to eliminate the annoyance of glare due to specular reflection. They should be of about middle value, that is, medium gray, and the floor should also be fairly dark.

The artificial lighting of picture galleries should be based upon the same fundamental principles as the natural lighting and fortunately it is not so difficult to control as is daylight. The artificial light should be of a spectral character which simulates that of daylight as closely as practicable. It may be directed from lighting units hung at the proper location as determined by the linear diagrams of incidence and reflection, and by the distribution curves of the units. It should be directed predominantly upon the hanging space. In the larger galleries the old system of trough lighting or continuous reflector is now primitive, unscientific and unsatisfactory. Such units may be hung from the ceiling or concealed behind architectural details. Artificial light may be projected through the sub-skylights upon the hanging space or through artificial clerestory windows high in the walls. Certainly, at this stage of the development of lighting, the defects of daylighting should not be perpetuated. For example, the flooding of diffusing sub-skylights by means of artificial light, though easy to do,

should be avoided when there are better ways of lighting paintings. In directing light upon the walls, care must be exercised in order that the light does not fall too vertically. Under such a condition, the frames and even the paint on some paintings cast undesirable shadows.

In the lighting of sculpture galleries the modeling of form by means of light is encountered. A very great expanse of overhead skylight produces a flat appearance. Sculpture requires a dominant light source. Several windows are usually unsatisfactory because of the multiplicity of shadows which result. An overhead skylight of moderate size provides a practicable solution of the lighting problem in sculpture galleries in which many objects are exhibited. It is the solid angle subtended at the object, rather than the actual area of the light source, which is important. The direction of light under these conditions cannot be altered for each object, but the object itself may be oriented and located with respect to the dominant light so as to be suitable in appearance.

Important pieces of sculpture may be placed in individual alcoves. If the latter are arranged in a series, each may be predominantly lighted by means of a high window opposite. The observer, in viewing the object, has the window at his back and high above him. The artificial lighting may also be accomplished by means of individual units. In any case, in the lighting of sculpture galleries, it is important that there be a very dominant component of light.

In large museums there are opportunities for constructing large interior rooms. This makes it possible to construct small rooms on the outskirts and thereby to utilize the windows where they are least objectionable. It has been proposed that these large interior galleries be lighted solely by artificial light. A continuous alcove could be erected around the entire room. The lighting could then be done efficiently by means of show-window lighting units concealed above the opening. The room proper could be high and of huge dimensions, and could be illuminated by chandeliers. The alcove could be separated, if desired, by balustrades.

Large armor courts, natural history exhibits and the like are best lighted by means of an overhead skylight. In the case of high rooms, this method is satisfactory for lighting tapestries on walls. By placing a sufficient number of lighting units above the skylight, and at a sufficient height above it, the spotted appearance of the skylight at night can be reduced. The lighting of the exhibits is more important than the appearance of the skylight. The best glass for the latter depends upon conditions, but in any case it should transmit light efficiently.

Those types of crystal glass which exhibit spread reflection are best. Examples of these are acid-etched, sandblasted, pebbled and wavy glasses. From the viewpoint of maintenance the last two are better because their surfaces are easily freed from dirt by washing.

Special units must be devised for special purposes. In an Egyptian room, for example, modern light sources may be adapted to fixtures of the proper period. Chandeliers and other visible fixtures possess possibilities if science and art are correlated in their designs.

Garden courts are a feature of modern museums. Single skylights are best for this purpose, because solar radiation must be admitted in sufficient quantities for the plant life to thrive. When artificial lighting is considered it appears logical to think of the appearance of a garden at night. Ornamental lamp-posts fit well into such a scheme.

Rooms in which display cases are located present difficulties in lighting, owing to the reflections from the glass surfaces. If all the cases are high, so that the observer views them from the side instead of the top, overhead skylight and artificial lighting units are satisfactory. Even windows in the side walls are not undesirable. However, if the cases are low and the contents are viewed through the top glass, it is difficult to light them so that the observer is not annoyed by the images of a light source reflected from the top glass. A room containing low cases of this character is best lighted by means of windows on one side. The observer is then able to find a position free from annoying reflections. The artificial lighting is fraught with difficulties. It is perhaps best done by means of show-case units inside the cases and indirect lighting of a moderate intensity obtained from units with opaque bowls hung from the ceiling. By the use of the show-case units the objects in the cases may be illuminated to such an intensity that the image of the ceiling reflected from the glass cover is not perceptibly annoying. An elaborate use of simple diagrams is essential in any case if satisfactory results are to be obtained. Such displays are perhaps the most unsatisfactory of exhibits in modern museums. It would help considerably if museum authorities would eliminate the low case wherever possible and would plan exhibits for the use of high cases so that objects could be viewed through vertical glasses.

The fading due to daylight has been touched upon elsewhere. Objects of delicate and fugitive colors can be lighted with greater safety solely by means of artificial light of an approximate daylight quality. The radiant energy which is responsible for fading is present in less amounts per unit of visible energy in the total radiation from tungsten daylight lamps than in natural daylight. In illuminating these objects of delicate

and fugitive colors, artificial light of just the desired intensity can be used. In extreme cases artificial light has the advantage that it may be shut off when no visitors are present.

Churches

The ancient heathen and Jewish temples were illuminated by daylight entering doorways and courts. The temple was not a place of worship in the modern sense but an abode of the god, where ceremonial rites were performed by the priest. The early ecclesiastical structures of Christian worship were not copied from the heathen or Jewish temples but evolved from a combination of a hall of justice and a market place. In these churches there was no emblem such as the cross, but the structures themselves were built in the form of a cross. The arms of the structure, forming a cross in plan, were called transepts. These arms intersected the longitudinal axis of the structure between the nave and the apse or choir. Over the intersection a central tower or spire was commonly erected. If there were no transepts, the nave would extend from the choir to the principal entrances.

Since the evolution of those early churches, creeds have multiplied in number and the structures have been influenced by the civilization of various nations. The result is that modern churches differ widely in style.

The lighting fixtures of a church must conform to the architectural style. Lighting effects must not only be "ecclesiastical" but must also be expressive of the general characteristics of the particular creed for which they are designed.

In attacking the problem of lighting a church, it is well to be familiar with the historical development of the style of architecture and with the creed, in order that the final lighting effects may not only harmonize with the spirit of the interior but actually enhance it. The lighting should be dignified, impressive and without annoyance to vision.

The intensity of illumination is of extreme importance and it should not ordinarily be as great as would be desired in other auditoriums. It is necessary that the congregation be able to read with comfort, but it should be noted that a dim light is conducive to a spirit of prayer and meditation. Dimmers or a number of circuits and switches should be available, in order to adjust the light to conform to the requirements of various parts of the ceremony. The spirit of a certain modern creed, for example, appears to demand more intense illumination and general lighting. Other creeds which are more severe require lower intensities of illumination and harsher effects. The dominant notes of the particular creeds should be sought out and expressed by means of light.

Even the charm and expressiveness of tinted light may be as effectively utilized as the expressiveness of distribution of light. Congruity should be the aim in relating lighting, architecture and creed.

In the study of church lighting the ceremonial uses of light should not be overlooked.

Many churches have ceilings of low reflection-factor and it is obvious that direct lighting units must be utilized in these cases. However, this does not mean that the light sources cannot be well screened from the eyes. Deep lanterns, large enclosed units with a dominant direct component, and prismatic enclosing glassware lend themselves to the solution of these lighting problems.

Architectural ornaments, domes, arches, etc., which are the parts of an architectural whole, can be individually lighted in a manner that causes the chief lines and parts to be modeled as the architect desires. Concealed lighting accomplishes this end very well. Lamps may be concealed above a capital, behind moldings and large cornices. Indirect lighting units may be suspended here and there. Some may illuminate the chief portion of the ceiling; others may light an archway or alcove. All these possibilities are available for the production of certain light-and-shade effects which harmonize with the architecture.

It may be safely stated that in those churches which do not have dark ceilings indirect and concealed lighting systems are in the ascendency. The reason is very plain, for these methods have the greatest possibilities of harmonizing lighting with architectural details.

If the chancel is to be lighted by means of windows, the latter should be very high and located at the sides if possible. Preferably they should be of rather deeply stained glass. It is easy to conceal light sources behind various projections near the front of the chancel and thereby obtain lighting for this portion of the church. Light sources can be concealed behind flower boxes and devices of this character constructed specially for the purpose of containing lighting equipment. In some cases the speaker has actually been spotlighted. The altar is very prominent in some churches and in these cases burning candles are used symbolically. In some instances miniature electric incandescent lamps surmounting imitation candles replace the wax candle. The high-voltage lamp with candelabrum base can be used for this purpose to some extent, but a transformer and miniature lamps of low voltage may be a better solution.

Much of the charm and effectiveness of fine churches may be attributed to the stained-glass windows which soften the glare of daylight. Beautiful church windows lose much of their charm at night. In a few instances they have been illuminated at night by means of light units

hung from the exterior of the church. This can scarcely be the best solution, for such windows require bright backgrounds which comparatively small lighting units do not supply.

There are special points of interest in churches which, if they are illuminated to a greater intensity than their environments, will be more conspicuous and perhaps will appear more significant and effective. Local lighting is apparently the best solution.

The organ keyboards should receive special lighting and this can be accomplished by means of simple metal shades. The switch should be convenient for the organist to reach. There are other similar lighting problems pertaining to the choir.

Modern churches have bulletin boards and most of these should be illuminated by artificial light. This is simply done by means of metal reflectors containing ordinary light sources.

COLLATERAL READING

Lighting of Public Buildings

TRUDELL, V., La Lumière Electrique au Theatre (H. Dunod & E. Pinat, Paris, 1914).

MARKS, L. B., The Lighting of Public and Semi-Public Buildings, The Brickbuilder (Sept., 1913 to Feb., 1914).

RAYNER, E. H.; WALSH, G. W. T., and BUCKLEY, H., The Lighting of Public Buildings, Ill. Eng., **15**, 108 (1922).

HYDE, E. P., The Lighting of the Cleveland Museum of Art, Trans. I. E. S., **11**, 1014 (1916).

The Lighting of Picture Galleries and Art Studios — A Symposium, Ill. Eng., **7**, 147 (1914).

KIRBY, G. T., and CHAMPEAU, L. X., New Developments in Art Gallery Illumination, Trans. I. E. S., **18**, 515 (1923).

MILLS, F. S., Lighting for Motion Picture Studios, Trans. I. E. S., **18**, 143 (1923).

LITTLE, T. J., JR., Semi-Public Lighting (by Gas), Proc. Intern. Gas Congress, 288 (1915).

CALDWELL, F. C., Good Lighting in the Schools, Trans. I. E. S., **15**, 321 (1920).

DATES, H. B., Practical Applications of the Principles of School Lighting, Trans. I. E. S., **17**, 642 (1922).

Code of Lighting School Buildings, Trans. I. E. S., **13**, 185 (1918); **18**, 577 (1923).

HADLEY, G. T., Illumination of a Masonic Hall, Elec. Rev. & West. Elec., **60**, 1167 (1912).

An Improved Method for the Illumination of Motion Picture Theatres, Trans. I. E. S., **15**, 645 (1920).

MCOMBER, L. W., Analysis of Moving Picture Theater Lighting, Elec. World, **68**, 122 (1916).

JONES, B., The Possibilities of Stage Lighting, Trans. I. E. S., **11**, 547 (1916).

GRUNSKY, C., The Lighting of a Museum, J. Elec., **40**, 228 (1918).

WILSON, W., The Electric Lighting of Ecclesiastical Buildings, J. Inst. Elec. Eng. (London), **56**, 193 (1918).

Lighting a Church of the Basilica Type, Elec. Rev. & West. Elec., **69**, 583 (1916).

Report of Lighting of Large Buildings Division, Proc. N. E. L. A., 380 (1922).

Lighting of Public Buildings, Ill. Eng., **15**, 135 (1922).

CHAPTER X

COMMERCIAL LIGHTING

[WARD HARRISON]

Offices and Drafting Rooms

Nature of Problem. — To-day there is no reason for other than the best illumination in new office buildings and in the older offices, although in the latter case the result is attained at a greater expense, for, in the majority of cases, some change in the location of outlets will be necessary. In general, however, the required alterations in wiring will be found profitable even where considerable expense is involved, *for there are no locations where the consequences of poor lighting are more serious or more keenly felt than in offices and drafting rooms.*

From the standpoint of utility, the problem of office lighting can be very simply stated. Fundamentally it is to provide the best illumination for sustained vision of flat surfaces in the horizontal or slightly oblique planes in which papers, books, photographs, etc., are usually examined. The perception of objects in their three dimensions, so important in the industries and in the arts, is here relatively unimportant. On the other hand, experience has shown that in offices and drafting rooms, perhaps more than in any other locations, an ample intensity of soft well-diffused light must be provided in order that discomfort may be avoided and that the eyes may not become excessively fatigued by close application for long periods of time. There should be no extreme contrast in the brightness of objects within the field of view; shadows should be subdued, if not entirely avoided; the lighting system should be designed to permit flexibility in the arrangement of office furniture; it should be easy of maintenance and satisfactory in appearance.

In designing a system of office lighting, it should be remembered that standards of illumination intensity are rapidly and continuously rising, as tenants and building managers come more and more to appreciate the value of good illumination. Furthermore, allowance should be made for the fact that, even in a small group of persons, one or more with defective eyesight will usually be found, and the lower limits of permissible intensity should not be approached so closely that unnecessary hardship is imposed on anyone. Again, it should be remembered that even where individual lamps are supplied for the illu-

mination of the desks, a general illumination over the entire room of at least 1 foot-candle should be provided.

TABLE XLVII

MAXIMUM RATIOS OF SPACING TO HEIGHT OF LIGHT SOURCE FOR SATISFACTORY OFFICE ILLUMINATION

System	Limits for One Row of Units	Limits for More Than One Row of Units	
	$\frac{A}{H}$	$\frac{B}{H}$	$\frac{C}{H}$
Indirect*..............................	1.3	1.5	0.6
Dense Semi-indirect*..................	1.2	1.5	0.6
Direct Semi-enclosing..................	1.1	1.4	0.5
Direct Dense Opal.....................	1.1	1.4	0.5

* With indirect or semi-indirect the ceiling is considered the light source.

In some buildings where careful attention has been given to the design of the lighting of offices and hallways, an annoying drop in intensity is frequently apparent when one steps into an elevator. The adaptation of the eye is not instantaneous, and a person going from one intensity to another naturally moves slowly and with caution. In large modern offices, the time of a very large number of persons is dependent to a considerable extent on the elevator service, and ample intensity of lighting of the cars should be a first consideration.

Effect of Color on Quantity. — The experience is not uncommon to those who occupy offices for which daylight furnishes illumination the greater part of the time, that, as the natural light begins to fail and the lamps are switched on, the artificial illumination is seemingly inadequate — although at night the light is entirely satisfactory. This is due in part to the fact that the eye is, at this time of day, suffering from a certain degree of natural fatigue, and in part to the disinclination of the eye to adapt itself to light of a lower intensity. Again, toward evening the horizon as seen through the windows is frequently even brighter than at midday and this, by contrast, makes the interior illumination seem even more inadequate. The difference in the color of artificial light and daylight also appears to be partially responsible for the same impression, and a combination of the two is displeasing to many. In such cases, daylight lamps, which give illumination like sunlight in color, are desirable.

Contrasts. — Extreme contrasts, such as those existing between the brilliant filament of a lamp in an open reflector and the general level

of brightness of a room, may produce marked discomfort. This is especially true in office lighting, where the position of a light source with respect to the eye must remain practically without change for considerable periods of time. Furthermore, nine out of ten semi-indirect glass bowls now on the market are of too light density and are therefore unsatisfactory. Heavy-density semi-indirect and totally indirect units not only overcome this objection, but at the same time minimize the specular reflection, or sheen, from books, paper, photographs, desk-tops, etc. In many cases desks are thoughtlessly given a high polish — not infrequently they are topped with plate glass — and in such cases the reflection of a source may approach in brilliancy that of the source itself. It is difficult to avoid reflections entirely, but the harmful effects can be minimized by employing only those units which are of low brilliancy, and by arranging them carefully with respect to the position of the desks, or *vice versa*. It is often possible, in the case of small offices where single desks are used, to arrange the desks along the wall so that those occupying the office have the light sources over their shoulders. In this way reflections from desk-tops are prevented and the walls, unless highly finished or hung with pictures framed behind glass, will not give rise to objectionable reflections. Side walls of considerable area should not be finished in a tint so near to white that they will reflect a large volume of light into the eye, nor should they be so dark as to cause undue contrast and needless absorption of light.

Shadow. — Although shadows are very helpful in determining the shape and relative proportions of objects, they are not strictly necessary for the usual office where the work is largely with horizontal planes. In fact, an excess of shadow is likely to prove a decided nuisance; only enough to show the natural appearance of objects and persons is necessary. Dense shadows, such as those cast by a single unit of high intensity and relatively small size, or shadows with a series of sharp edges, such as those cast by several small units, are particularly annoying. To be satisfactory from a shadow standpoint, light sources should be of large area and low brilliancy, in order that such shadows as do form will be luminous and with gradually fading edges.

It is of particular importance in the case of drafting rooms that the light be highly diffused in order that shadows and reflected glare may be avoided. It will often be found more satisfactory from a lighting standpoint, and just as satisfactory from other standpoints, to work upon the dull side of tracing cloth rather than upon the shiny side.

From the data presented in the preceding paragraphs, and a careful

review of Table XXXIII, page 282, the following conclusions may be derived:

1. Open-reflector units are not suitable for large general offices from the standpoints of brightness, specular reflection or shadow. A single direct-lighting unit, if of large area and low brilliancy, would be satisfactory for one person alone in an office when so located as to bring the light over the left shoulder. It should be designed to illuminate the surroundings to a fair intensity.

2. Semi-enclosing units are preferable to open-reflector units for office and drafting-room lighting. It is important that they be of large size and that the density of the glass bowl be such that they are satisfactory from a brightness standpoint. Care must be used to place them so that specular reflection toward the eyes will be avoided as far as practicable. Semi-enclosing units are usually the best solution of the problem where it is actually impossible to obtain a light ceiling.

3. Semi-indirect units which have a high brightness due to the use of light-density glass bowls of small diameter produce somewhat the same general effect as direct lighting units. Where the ceiling does not present a reasonably good reflecting surface and where it cannot be made into a good reflector, *semi-enclosing* units are, however, more efficient than such *semi-indirect* units and are equally good in most other respects. Where a ceiling of reasonably good reflecting power is obtainable, units of lower brightness are to be preferred. In other words, the legitimate field for the ordinary light-density semi-indirect unit as applied in office lighting is extremely limited.

4. Semi-indirect units of dense glass or lighter bowls of large area and totally indirect units are excellent for office lighting where a ceiling of good reflecting power is obtainable. Brightness contrasts can be made entirely satisfactory, specular reflection is reduced to a minimum and objectionable shadows are avoided. A lighting system of such units permits maximum flexibility in the arrangement of furniture in a general office and is usually the most practical system for a private office as well.

Obviously, it is important that whether indirect, semi-direct or semi-enclosing units are selected, there should be no unnecessary waste of light due to improper design. Whether the reflector is of mirrored-glass, opal, porcelain or other material, it should be designed to permit easy cleaning and should be hard and smooth in order that it may serve as a good reflector and be slow to accumulate dirt; the contour should be such that light will not be pocketed and lost.

Location and Number of Lighting Units. — In any case, but particularly in the case of offices built for renting purposes, careful considera-

tion should be given to locating the units in such a way that if partitions are later removed or new ones built in to suit the requirements of a tenant, the outlets already installed will still be usable. This factor alone is frequently of sufficient importance to justify the use of a greater number of outlets than are necessary to suit the existing lighting requirements. Special structural features, such as the location of ceiling beams and the placement of doors and windows, should receive attention. The sketches of Fig. 119. illustrate how the use of 6 units, in a room where 4 would satisfy conditions of uniformity, permits the change from a general office to a private one, where, owing to the location of the windows, a change to two offices of equal size would be

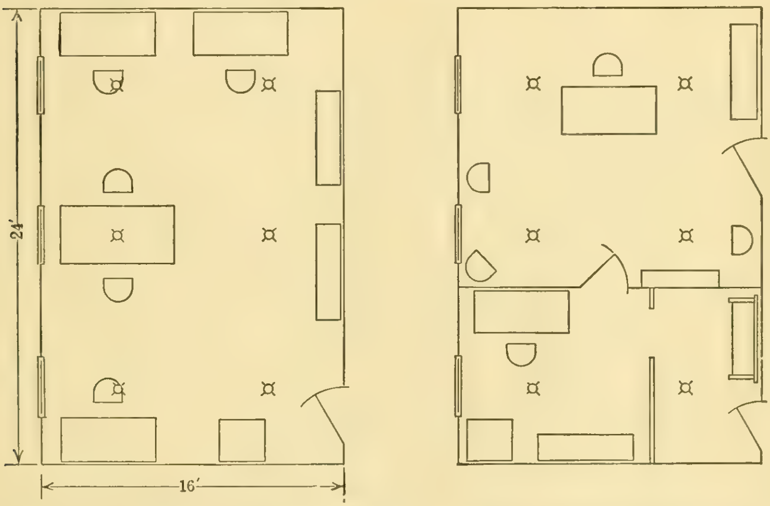


FIG. 119. Location of Outlets Should Provide for Possible Changes in Office Arrangement.

practically out of the question. The cost of installing, say, 6 units, need not necessarily be much greater than that for 4, for the cost of glassware increases, not in proportion to its diameter, but at a much faster rate, and the difference in its first cost may be sufficient to offset the greater cost of wiring. It is an advantage, too, if the number of different sizes of units and lamps employed in an office building can be kept small in order to facilitate replacement from stock. Sometimes it is advisable to wire for locations where it is thought units may at some future time be desirable, but to seal the wires beneath the plaster until required.

Where totally indirect or dense semi-indirect units are used, and the greater part of the illumination comes from a large area on the ceiling,

the question of direct glare is automatically cared for. On the other hand, because of the large ceiling area which is brightly lighted with such units, it is difficult to avoid a certain degree of specular reflection in polished surfaces. Reflected glare from direct lighting equipment can sometimes be avoided, as previously stated, by arranging the desks along a wall so that specularly reflected rays will travel away from the eye, rather than toward it, as shown in Fig. 120.

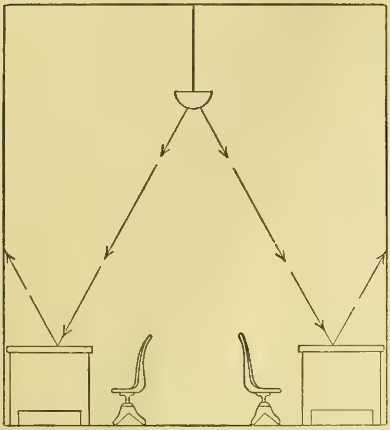
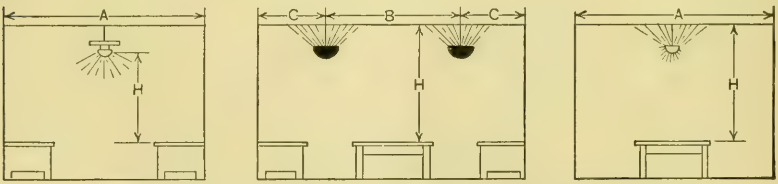


FIG. 120. Arrangement of Desks to Avoid Specular Reflection.

From a study of the light distribution of units with special reference to office lighting, it has been possible to establish fairly definite rules for determining the number of rows of units required, the spacing distance between units, and the distance from the walls to the nearest rows of units, to insure a satisfactory illumination as regards both quantity and direction in all parts of the room. The data given in Table XLVII, see also Fig. 121, have been applied very satisfactorily in practice.



With indirect or semi-indirect the ceiling is considered the light source.

FIG. 121. Diagrammatic Sketch for Spacing and Heights of Office Units.

Libraries. — The problem of lighting the reading room in a library is not dissimilar to that of lighting a large general office, and if an overhead lighting system is desired the same rules apply; however, in many cases a preference is expressed for individual tables and a very low degree of general illumination in order to promote an atmosphere of quiet. Individual lamps, however, must be chosen with extreme care so that glare may be avoided, and must be placed to one side of the reader and not more than one foot in from the edge of the table if there is to be an absence of specular reflection from the books. Where individual tables

are used these principles can be carried out, but a satisfactory system of local lights for large reading tables accommodating four or more persons can scarcely be provided.

Store Lighting

Classification. — For consideration of their lighting requirements, stores may be divided into four classes:

1. Department stores and the large specialty stores of principal cities;
2. Medium-sized stores, including the large stores of smaller cities;
3. Small, select stores and shops;
4. Small stores of the usual type.

In the stores of the first-named class, the lighting requirements are very similar, although the location of stores, their size and the individual preferences of their owners will, of course, cause considerable variation in the design of lighting installations. Such stores are usually imposing establishments and the lighting equipment should assist in furthering the impression created by the store as a whole. On the main floor, especially, a high intensity of light and a pleasing appearance of equipment are necessary.

For stores of medium size, in which class it will be noted are included the large stores of the smaller cities, the system provided should possess distinctive and decorative features, but these should be obtained with due regard to the efficient utilization of the light.

In the select small store or shop, great freedom is usually permissible in the selection of a lighting system; good appearance and a pleasing effect are the important considerations.

For the usual small store, elaborate lighting is not required; rather, the system should supply plenty of light efficiently.

Department and Large Specialty Stores. — For the main floor of a department or large specialty store, a system of enclosing units or of some form of semi-indirect or totally indirect units is preferable to a system employing open reflectors. With the exception of certain prismatic types and flattened globes, totally enclosing units do not provide a high degree of light control, and in order to avoid undue glare the units should be of large area and highly diffusive. A portion of the light from these units is transmitted directly to the objects beneath and another portion reaches them by reflection from the ceiling. A certain percentage of the light flux is emitted at angles near the horizontal and never reaches the counters. Light emitted near the horizontal does, however, serve a very useful purpose in that it illuminates vertical or

inclined surfaces, such as shelves, racks, etc., which if lighted only from directly above would be inadequately illuminated. Enclosing units are obtainable in a wide variety of shapes and sizes, ranging from very inexpensive to very costly and exclusive designs, which features have led to their common use in all classes of stores.

Indirect Units. — For comfortable vision, indirect and semi-indirect units are more desirable for the main floors of department stores than are enclosing units. With strictly indirect systems, where the ceiling acts as the light source and there is a pronounced downward direction to the light, the uniformity and diffusion of the illumination are excellent, glare from the light source is absent, and reflections from plate glass and polished fixtures are avoided; however, shadows, which if of proper density are a great aid in judging the shape and proportions of an object, may be too greatly reduced. The direction of the light, moreover, tends to make vertical surfaces appear poorly lighted. Since the illumination of the room is entirely dependent upon reflected light from the ceiling, the efficiency of the system will be highest if the ceiling is finished in white. However, with the present low cost of light, a tinted ceiling is justified where it is essential to the decorative scheme of the room or where lighting of a certain color tone is desired.

The luminous-bowl type of indirect unit produces the same general character of illumination as that produced by strictly indirect units; but the auxiliary bowl, being luminous, gives a direct component which assists slightly in illuminating vertical surfaces.

Semi-indirect Units. — Semi-indirect units of dense or toned glass give an effect very similar to that given by luminous-bowl indirect units, but they transmit a higher percentage of the light, and are, under usual conditions, slightly more efficient. With bowls of light density, the results approach more nearly those obtained from opal-glass enclosing units; contrary to what might be expected, however, the semi-indirect system is often more efficient, owing to the fact that less light is absorbed by the bowl, less light is emitted in angles near the horizontal, and more light is directed to and diffused from the ceiling at effective angles.

It is possible to obtain either indirect or semi-indirect bowls in exclusive designs harmonizing with the decorations and conforming to the tastes of the user. Regardless of the design of the exterior, however, it is of the utmost importance that the interior be a hard, smooth, reflecting surface in order that good efficiency may be maintained. In an installation which runs into any considerable expenditure, it is well worth while to secure the opinion of a competent architect or decorator before determining upon a definite exterior design. Frequent cleaning

and good maintenance are very essential for these types of lighting equipment.

Upper Floor Requirements. — Lighting units of the general type mentioned are suitable for the upper floors of large stores; often a smaller size of the same design may be chosen. In some cases, a well-designed direct lighting system may meet the requirements satisfactorily. With open reflectors, bowl-enameled lamps should always be installed and the units should be suspended at such a height that they will be, as nearly as possible, outside the ordinary range of vision. Tungsten lamps larger than 200 watts should not be used in open reflectors. Semi-enclosing units are available, however, which operate on much the same principle as an open reflector but which are provided with a diffusing glass bowl below the reflector which screens the lamp from view. With such units, any size of lamp may be used. Their efficiency compares favorably with that of the prismatic type of enclosing unit.

On all floors, the fixtures should be located symmetrically with respect to the divisions or bays usually formed in the ceiling by the structural features of the building, unless it is desired to arrange the lighting to enhance some architectural effect in light and shade, or color, in accordance with a skillful designer's well-considered plan.

Stores of Medium Size. — The lighting requirements of stores of medium size are the same as those cited for large stores, except that a location amid less impressive surroundings may decrease the need for purely decorative features. In this class of store, a semi-indirect system employing some form of inexpensive medium-density bowl will often fully meet the requirements of a distinctive and economical installation. A well-designed direct-lighting system, such as might be used on the upper floors of a large store, is very frequently deemed entirely satisfactory — especially where a semi-enclosing unit is used.

Exclusive Stores. — Exclusive small stores or shops, found principally in the larger cities, lend themselves to an artistic treatment which is impossible in large stores. In many cases, the use of colored lamps to provide lighting of a distinctive tone is highly desirable, while uniformity of illumination is to be avoided rather than sought. The fixtures may well be of special design, but care should be taken to avoid the very common error of allowing too brilliant light sources within the range of vision. Modifications of semi-indirect, indirect and enclosing fixtures are used almost entirely.

Small Stores in General. — Efficiency is the first requirement of a lighting system for the usual small store. A high intensity is necessary for the convenience of customers and for advertising purposes, but the fixtures may be of very simple design. Consequently, direct lighting

with open reflectors, or with a good type of semi-enclosing unit, is, as a rule, most applicable, although often the installation of an inexpensive semi-indirect or enclosing unit is preferable.

Semi-enclosing units possess an advantage over open reflectors in that they diffuse the light from the filament over a comparatively large area; hence, they may be used with a lamp of any size and in locations where open reflectors would cause annoying glare. They possess an advantage over opal enclosing units in that they distribute light in much the same manner as a dense-opal open reflector and are, therefore, less dependent for their efficiency upon the finish of the walls and ceiling.

A common mistake in the lighting of small stores is the installation of a single row of direct lighting reflectors along the center of the store, where at least two rows of smaller units should be used to prevent the customer's shadow from interfering with the examination of the wares, and to illuminate the shelving or high cases along the side walls. A single row of semi-indirect or enclosing units is, however, usually satisfactory. An exception to the use of bowl-enameled lamps with open reflectors may be made in the case of small jewelry stores, where brilliant reflections in gems and cut glass may be desirable; the units should, however, be placed well above the usual line of vision, to avoid glare.

Illumination Intensities. — A lighting installation serves a double purpose: first, it permits the merchandise to be examined with comfort; second, it advertises the store. Light is recognized as one of the least expensive and most effective of advertising media, and hence intensities higher than those absolutely necessary for comfortable vision are almost universally demanded. The three factors which govern the selection of an intensity for any particular case are: the nature of the merchandise — for dark goods require a higher intensity than light goods to appear equally well illuminated; the illumination standard of the immediate neighborhood; and, the amount which the owner feels it expedient to apportion for the advertising value of a high intensity. The lower values of any table of intensities should, therefore, be used cautiously and full weight given to local conditions. However, values applying to average conditions are useful as a basis upon which to estimate desirable intensities, and such values are given in Table XXXII (Chapter V).

The maximum ratios of the spacing distance, to the height of the unit above the working plane, which may be used with fair uniformity of illumination are given in Tables XXXIX and XL. If greater spacing distances than those determined by these ratios seem desirable, it should be remembered that as the spacing is increased, the degree of uniformity decreases rapidly. The greater the permissible spacing

distance, the larger the lamps which may be used and the fewer the number required. The fewer the units of a given type, the less the installation and operating expense, but the greater the area affected by the failure of a lamp and the denser the shadows.

Show-windows

The primary object of a show-window is to attract attention, and the realization of this object depends upon lighting. It should be obvious that the show-window provides opportunities to utilize all the powers of light. Not only may the displays be flooded with light, but spectacular effects may be utilized for their attention value. The show-window in many respects may be likened to a stage. In fact, there is such a similarity that it may be stated that all the lighting effects of the stage may be utilized in the show-window.

The intensity of illumination in the show-window must be greater than that in the street or in the store if it is to attract much attention. The minimum intensity which is satisfactory varies considerably with the location. It may be ten times as great in the downtown district along a " white way " as in the case of a store in the suburbs or in a village. The light sources should be concealed if the display is to be easily seen. It appears to be the idea of many second-rate shopkeepers that a great many bare lamps, plainly visible, provide good lighting. They may attract attention but they do not illuminate a display satisfactorily.

The use of border lights along the top of the window is the most common device. The type of reflector is determined by the depth from front to rear and the height of the show-window. By drawing an elevation to scale the type of distribution curve may be determined. Reflectors for this purpose are chiefly of silvered and prismatic glass, and they are designed to give an asymmetrical distribution. The spread of the curve is determined by the vertical cross-section of the window. Very high and shallow windows require a more extensive distribution. The watts per running foot of window depend upon the intensity of light desired and vary from 20 to 300. The manufacturers of equipment of this character supply the necessary data from which computations and selections can be made. A practicable scheme, which is useful for computing the lamp wattage per running front foot for gas-filled tungsten lamps, but which does not allow for color effects, is as follows:

Classify the window, giving it a number from 1 to 10, depending upon its importance, the goods displayed, the location, the street

lighting intensity, etc. For example, a window in a country store will be classified as number 1. The windows in high-class stores in the shopping districts of cities would be given number 10. However, inasmuch as there is a tendency toward higher intensities of artificial light, the best windows of first-class department stores may eventually be given a number greater than 10. Now add the distance in feet from the floor of the window to the point where the lamps are to be mounted to the distance in feet from the glass to the back of the window. Next multiply this sum by the classification number of the window. The result is the lamp wattage required per running front foot of window. This rule applies to the gas-filled lamp. If " daylight " lamps are used the wattage should be increased by 50 per cent. After obtaining the watts per front foot the total wattage is found by multiplying this value by the total frontage of the windows. This total wattage may then be distributed among a certain number of lighting units. Although the use of individual units consisting of high-efficiency lamps in silvered or prismatic glass reflectors is generally advisable, there are places for other equipment. Aluminized and enameled reflectors reflect light but they do not direct it as do the silvered and prismatic reflectors. However, these units may be used to advantage where diffusion rather than projection of light is desired. Trough reflectors, though not very effective as projectors of light, meet many special needs. Many of the necessary data pertaining to this equipment can be obtained from manufacturers.

In some windows, footlights are used in addition to top lights. These can be ingeniously concealed. They provide light from below and reduce the shadows sometimes too apparent when only top lights are used. The next step is to add sidelights. Where the window runs around a corner it is necessary to resort to stationary screens or some other device to conceal the light sources from view.

More than one circuit is installed in some of the modern show-windows in order to utilize the charm of colored light and to obtain a variety of lighting effects. At present it is usually necessary to use colored screens in frames supported by the reflectors. Devices of this character are on the market.

The lighting units in a show-window are concealed behind structural features designed for the purpose, or a valance is provided at the top of the window. The background of a show-window should have a dull finish in order not to act as a mirror and reflect images of the light sources into the eyes of the observer. Glazed surfaces of wood, metal or glass are objectionable for this reason. If windows are necessary in the background in order to admit light into the store, draperies can

be drawn before them at night. Backgrounds of moderate reflection-factor are preferred to those of high or low value.

A high intensity of illumination is desirable not only for the purpose of attracting attention but also to make it possible to discriminate colors, texture, etc. It is unsatisfactory to the observer not to be able to see the display sufficiently well to appraise the goods. Tests have indicated a greatly increased drawing power for windows where the illumination has been increased. One set of data showed a 33 per cent increase in drawing power where the illumination was changed from 15 to 40 foot-candles and a 73 per cent increase by the use of 100 foot-candles. At the same wattage, the use of colored light increased the drawing power about 40 per cent. The daylight lamp reveals the colors satisfactorily, but in some cases, by comparison with artificial light of yellowish tints, the windows lighted by means of the tungsten daylight lamp may appear " cold." This may be remedied by using backgrounds and floor coverings of warmer tints than would ordinarily be used.

Overhead skylights are used to some extent in deep, low windows and in " island " windows. Perhaps the best solution for the artificial lighting in these cases is to set pieces of etched or sandblasted crystal glass into recesses in the ceiling. A light source may be placed in a reflector or enclosure above each of these pieces of glass. If daylight is to be admitted from above, allowance must be made for this.

If there were no considerations other than lighting, an ideal show-window would have several circuits completely around the window. These would be controlled by dimmers and switches so that any desired quality and dominant direction of light could be obtained. The background would be removable so that any scenic representation could be used. This scene would be provided with lighting from concealed sources, and the quality of light would be under control. In brief, this includes the possibilities discussed in connection with stage lighting. The arrangement for changing the scene is desirable because goods are often displayed out of season. For example, furs are shown in August when the need for them is remote. The power of suggestion might be utilized by means of a wintry scene in the background. Special lighting of this scene adds greatly to its effectiveness. By no means has the show-window reached its highest state of development.

Spotlights are very effective in show-windows. They pick out a single article and emphasize it amid the semi-darkness. Flashers may be used to control several spotlights in a single window. If these are lighted in succession, the pointing " fingers " of light are very effective in directing attention.

Portable lamps and artistic lighting fixtures also have a field in the show-window. They aid in simulating interiors and can be used for concealing light sources which provide the primary lighting.

The daylighting of show-windows is most generally accomplished by means of a vertical plate glass, but various refinements may be incorporated. The opaque background of the show-window prevents light from entering the front part of the store. In order to overcome this objection, windows (usually decorative) are sometimes placed in the background. As already suggested, it is well in many cases to provide draperies for them at night in order to eliminate the reflection of images of the light sources. Special prism glass is sometimes placed in the upper part of the window or above it, in order to direct light into the back of the window or into the store. Overhead skylights are sometimes installed in the ceiling of the show-window.

Curtains and awnings are used for protection against intense sunlight, and the awnings are also used to reduce the annoyance from images of the sky and buildings reflected from the vertical glass. These reflected images are extremely annoying; and while they cannot be avoided in the case of the vertical glass, because the images of the sidewalk, street and opposite buildings are always present, their effect can be minimized by the use of sufficiently high intensities of illumination on the articles exhibited. In one case experiments showed that with a 100-foot-candle illumination, due to daylight, on the window surface, the addition of from 200 to 300 foot-candles made the interior as distinctly visible as when the artificial lights were extinguished and the plate glass in the window removed. It required, however, the addition of about a 1000-foot-candle illumination to make the window display attractive. This was accomplished by the use of spotlights or floodlights of roughly 25,000 candlepower each. Where such intensities are employed, care must be taken to see that the additional heat does not injure the display.

If the exterior objects were non-reflecting, there would be no visible reflected images. Certain schemes using a curved glass instead of a vertical plane glass have been tried but have not come into general use, possibly because the use of curved glass requires that its lower edge be placed back from the ordinary front line of the window and hence the goods displayed must be put farther back than usual and receive less natural light, as well as being farther from the observers.

COLLATERAL READING

Commercial Lighting

HARRISON, W., Lighting of Offices and Drafting Rooms, Elec. Rev. (U. S.), **72,** 864 (1918).

POWELL, A. L., and ALLISON, H. H., Lighting of Hospitals and Dental Offices, Elec-Rev. (U. S.), **77,** 400, 553 (1920).

HOEVELER, J. H., and BUTLER, H. D., Illuminating a Drafting Room, Elec. Rev. & West. Elec., **63,** 929 (1913).

Indirect Illumination of a Drafting Room, Elec. World, **60,** 832 (1912).

KIRLIN, I. M., High Intensity Illumination of Office Buildings, Elec. Rev. (U. S.), **79,** 235 (1921).

POWELL, A. L., Modern Office Lighting, Elec. World, **73,** 316 (1919).

WISE, A., Modern Practice in Office Lighting, Ill. Eng., **12,** 27 (1919).

SCOFIELD, T., and FOGG, O. H., Office and Store Lighting, Proc. Intern. Gas Congress, 166 (1915).

MOULTON, W. R., The Lighting of Stores and Public Buildings, Elec. Rev. & West. Elec., **68,** 918 (1916).

The Lighting of a Large Department Store, Lighting Jour., **3,** 245 (1915).

POWELL, A. L., Store Lighting, Lighting Jour., **1,** 90, 122, 142 (1913).

DANIELS, J., Notes on Department Store Illumination, Trans. I. E. S., **15,** 709 (1920).

POWELL, A. L., A Ten-Year Advance in the Illumination of Small Stores, Trans. I. E. S., **17,** 289 (1922).

HARRISON, W., and SPAULDING, H. T., Overcoming Daylight Reflections in Show Windows, Trans. I. E. S., **17,** 677 (1922).

STURROCK, W., and SHUTE, J. M., Effect of Light on the Drawing Power of the Show Window, Trans. I. E. S., **17,** 683 (1922).

Report on Illumination of Show Windows, N. E. L. A. Bull., N. S., **7,** 860 (1920).

CHAPTER XI

INDUSTRIAL LIGHTING

[H. H. MAGDSICK]

Factory Lighting

Factory lighting is an economic problem. In solving it one is concerned first of all with the provision of lighting conditions which will enable the eye to function most quickly and easily. Psychological factors in lighting are an important element in the efficiency of factory operatives, but aesthetic considerations are here of minor importance as compared with some other fields of illumination. The major requirements which must be met in the choice of lighting equipment and the design of the installation are a steady light of sufficient intensity on all work surfaces, whether in horizontal, vertical or oblique planes; a comparable intensity of light on adjacent areas and on the walls; light of a color and spectral character suited to the purpose for which it is employed; freedom from glare and from glaring reflections; light so directed and diffused as to avoid objectionable shadows or contrasts of intensity; a system which is simple, reliable, easy of maintenance and reasonable in initial and operating cost. With these requirements met, there result lessened eye fatigue and conservation of the vision of the employees; protection from accidents; greater production per operator; less spoilage and work of higher quality; improved morale and lesser turnover of labor; easier supervision and greater order and neatness in the plant.

The state is interested in the protection of employees against accident and impairment of vision. The statistics of insurance companies dealing in accident liability show that in a considerable proportion of all industrial accidents — nearly one-fifth — insufficient or incorrectly applied illumination is either the primary or a contributing cause. A growing number of states are, therefore, regulating the minimum amount of light to be provided and to some extent its quality. The code sponsored by the American Engineering Standards Committee and prepared under the direction of the Illuminating Engineering Society forms the basis of most of the state laws. It makes the following minimum provisions as to amount of light:

Rule 1. *Illumination Required.* — The illumination maintained shall be not less than given in the following table:

TABLE XLVIII

		Minimum foot-candles on the space or at the work
(a)	Roadways; yard thoroughfares	0.02
(b)	Storage spaces; aisles and passageways in workrooms excepting exits and passages leading thereto	0.25
(c)	*Where Discrimination of Detail Is Not Essential* Spaces, such as: — Hallways, stairways; exits, and passages leading thereto; toilet rooms; elevator cars and landings. Work, such as: — Handling material of a coarse nature; grinding clay products; rough sorting; coal and ash handling; foundry charging.	0.5
(d)	*Where Slight Discrimination of Detail Is Essential* Spaces, such as: — Stairways, passageways and other locations where there are exposed moving machines, hot pipes, or live electrical parts. Work, such as: — Rough machining, rough assembling; rough bench work; rough forging; grain milling.	1
(e)	*Where Moderate Discrimination of Detail Is Essential* Work, such as: — Machining; assembly work; bench work; fine core making in foundries; cigarette rolling.	2
(f)	*Where Close Discrimination of Detail Is Essential* Work, such as: — Fine lathe work, pattern making; tool making; weaving light-colored silk or woolen textiles; office work; accounting; typewriting.	3
(g)	*Where Discrimination of Minute Detail Is Essential* Work, such as: — Watchmaking; engraving; drafting; sewing dark-colored material.	5

As to the quality of light the code provides:

Rule 2. *Avoidance of Glare, Diffusion and Distribution of Light.* — Lighting whether natural or artificial shall be such as to avoid glare, objectionable shadows and extreme contrasts, and to provide a good distribution of light; in artificial lighting systems, lamps shall be so installed in regard to height, location, spacing and reflectors, shades or other suitable accessories, as to accomplish these objects.

Bare light sources, such as exposed lamp filaments or gas mantles, located within the ordinary field of the worker's vision, are presumptive evidence of glare.

Illumination of the Work. — The above provisions are suggested merely from the standpoint of protection to the eyes and to the life and limb of the worker. The required values of intensity are not offered

by the states as sufficient for efficient production; they do not take into account the economic factor, which is of interest alike to the manufacturer and his employees and which has been taken into account in Table XXXII, Chapter V.

It is significant that those factory managements which have given the most study to the lighting of their plants are tending in their practice toward higher levels of illumination.

The results of some quantitative tests in factories are indicated in Table XLIX.

TABLE XLIX

Illumination–Production Economy Tests

Shop	Average Foot-candles with Old System	Average Foot-candles with New System	Increase in Production with New System	Lighting Cost in Per Cent of Payroll
Pulley finishing......	0.2	4.8	35.0%	5.0%
Soft-metal bearing...	4.6	12.7	15.0%	no data given
Heavy steel machine..	3	11.5	10.0%	1.2%
Carbureter assembly.	2.1	12.3	12.0%	0.9%
Jute spinning........	1.5	9.0	17.0%	no data given
Plant mfg. elec., gas, and sad irons......	0.7 (4.0 at tool pt.)	13.5	12.2%	2.5%
Semi-automatic buffing brass shell sockets............	3.8	11.4	8.5%	1.86%
Mfg. piston rings.....	1.2	18.0	25.8%	2.0%
Letter separating....	3.6	8.0	4.4%	0.6%
Roller bearing.......	5.0	20.0	12.5%	2.4%

It will be seen that in all of these cases the advantage gained in decreased cost of production is far beyond the increased cost of lighting.

In a consideration of the amount of light necessary for factory illumination, all work surfaces must be considered, whether in horizontal, vertical or oblique planes. At one time, consideration was largely confined to light on the horizontal; yet most factory work involves the perception of objects in their three dimensions, and the illumination of all surfaces is important.

Except in especially unfavorable locations, such as near the dark side wall of a room, any of the systems of lighting usually employed can be expected to provide an intensity of illumination on any vertical plane equal to about one-half of that measured in a horizontal plane at the same point. This fact should be kept in mind, particularly in designing a lighting system to comply with the State Codes, which usually specify

only the value to be provided on the principal plane of the work, which may be vertical, horizontal or oblique.

Illumination of Surrounding Surfaces. — Moderate intensities of illumination in aisles and other spaces intermediate between the working surfaces, on the walls, etc., are necessary to safety, good vision and a stimulating atmosphere. Light side walls are conducive to a cheerful impression of brightness throughout the room. Sources which direct considerable light to the vertical planes, and light colors for the upper walls, aid materially in accomplishing this.

The eyes of the workman looking up from his well-illuminated machine or bench are not adapted for vision at low intensities; hence, if adjacent objects and aisles are only dimly lighted, he will be compelled to grope about, losing time and risking accident, or to wait until his eyes have become adapted to the low intensity. Glancing back at his work, he again loses time while the pupils of his eyes adjust themselves to the increased amount of light which reaches them. If long continued, this condition leads to fatigue, as well as to interference with vision, and to accidents. The general illumination of all intermediate and surrounding areas should be sufficient to allow no marked contrast with the brightness of the working surfaces.

Direction and Diffusion of Light. — Differences in brightness of surfaces, that is, light and shadow, are essential in observing objects in their three dimensions. Without such differences, except as variations in color are present, no outlines, edges or contours would be defined; one could not tell whether the faces were flat, convex or concave. On the other hand, in the factory it is usually necessary to work on surfaces in many planes; hence, while dense, sharp shadows would define edges and outlines most distinctly, they might also be so dark as to interfere with work in the shaded areas.

In offices, close scrutiny is largely limited to plane surfaces and the printed words and figures are rendered legible by differences in color and contrasts in brightness with the background, and here specular reflection and shadows are of no aid to vision, but usually do harm. Most factory operations, however, involve viewing objects in three dimensions.

For satisfactory general illumination in industrial plants, there must be no shadows so dense as to make vision difficult where the direct light from one or two sources is cut off, nor so sharply defined as to cause confusion between a machine part and its shadow. In general, lighting should be so designed that shadows are present, but they should be soft and luminous.

Color Quality of Light. — The spectral character of light used for industrial processes has an importance depending upon the nature of

the task and the shop personnel. When objects having color differences are involved, color identification and discrimination form an important aid to vision. They define outlines and edges and serve to identify objects which may be similar in other respects, such as form, texture and reflection-factor. For many industrial operations, therefore, it is necessary to provide an illuminant which emits rays of all colors, as is the case with gas and electric incandescent lamps. Where manufacturing processes require more precise color identification, a further correction, such as is provided in the "daylight" lamps, is found desirable, and for dye making and the closest color matching, the lighting equipment must duplicate the standard north skylight with exactness. There are, of course, numerous industrial processes in which little color discrimination is involved.

Under certain conditions the spectral character of the light is important from the standpoint of the penetrating power of the various wave-lengths. Thus, in a foundry, light in which red and yellow rays predominate is most effective during certain periods of the day's operations.

Glare. — Glaring light sources are frequently the cause of accidents; they interfere with vision, cause annoyance, discomfort and fatigue.

Wherever highly polished surfaces are present, the reflected images of a light source, as seen in these surfaces, are likely to cause more discomfort than the source itself. This is because of the necessity of directing the eye toward the work surfaces, and further because of the relative sensitiveness of the eye to light rays entering from below. In choosing lighting equipment it must be borne in mind that, although a given reflector may afford adequate protection against direct glare from the filament, it will not protect against glaring reflections unless the lamp is shielded in such a manner that it is not glaring when viewed from directly beneath. There are certain industrial operations, such as the inspection of finished surfaces, in which a certain degree of specular reflection or sheen is very effective in facilitating the process.

The ideal source for most factory lighting must be low in brilliancy, to minimize glare and specular reflection, and must distribute the light in a manner to supply satisfactory illumination on the vertical as well as on the horizontal. It must be sufficiently large in area to give soft shadows, and in most cases must be small enough to insure a directed light.

The Design of a Factory Lighting System. — The first provision to be made in the lighting of a factory is that of good daylight facilities. Where conditions permit the use of saw-tooth sky windows, the excellence and uniformity of daylight illumination near the windows is of

a very much higher order than that through the center of the shop. This may be overcome to some extent through the use of prismatic glass in the upper part of the windows, so as to redirect the daylight toward the center of the room. Glare should be avoided for those workers who must face the sky for long periods and for those who may at any time be subjected to direct sunlight, through the use of window shades. In order to utilize better the available daylight and permit the maximum intensity to reach the center of the room while still shading operators near the windows, it is especially important to have shades which may be drawn over the lower part of the window only. Window shades should be translucent rather than opaque.

For the artificial lighting of factories three types of illuminants are in use to-day — incandescent electric, incandescent gas (as well as a few open gas flames) and mercury-vapor arcs. In the choice of an illuminant one should consider the relative efficiency of light production, not only initially but especially throughout life. The latter is a point on which full information should always be obtained. One should further consider the effectiveness with which the light can be utilized. In this connection the range of available sizes is important, as is also the adaptability to control of distribution and quality of the light through accessory equipment. Spectral character of the light, convenience factors, fire hazard and other items enter. In determining the relative cost of lighting systems three items must be included: (1) Fixed charges, which include interest on the investment, depreciation of permanent parts, cleaning and other expenses which are independent of the hours of use; sometimes this item forms the greater part of the total operating expense; (2) maintenance charges, which include renewal of parts, repairs, labor and all costs, except the cost of energy, which depend upon the hours of burning; (3) the cost of energy, which depends upon the hours of burning and the rate for gas or electricity.

From the discussion of factory lighting requirements, it is apparent that the early practice of lighting industrial operations largely with light sources at the work itself will not provide satisfactorily for all requirements. There are, of course, some operations which require an exceedingly high intensity at the point of the work, and this intensity can be satisfactorily and most economically applied with small units lighting restricted areas. When such units are employed they should be, as far as possible, permanently fastened in the correct position. Special care must be exercised in shading them to protect the eyes not only of the operator but also of all the people in the room. To avoid objectionable contrasts in intensity, general overhead illumination should be provided in considerable amount. The higher the values of

the local illumination required, the greater must be the illumination of the surrounding surfaces.

As practice has tended toward higher and higher values of general illumination, the necessity for local supplementary lighting equipment has rapidly decreased. In a large proportion of typical modern manufacturing spaces, the absence of overhead obstructions and the arrangement of processes is such that a symmetrical installation of lighting units may be made, giving substantially uniform values through the room or working areas. This arrangement permits the maximum flexibility in rearranging processes and machinery. In other plants the presence of shafting, belts and other overhead obstructions, and a fixed arrangement of the plant facilities make it desirable, while still providing general illumination from overhead, to locate the rows of units so that there will be the greatest freedom from shadows and the highest utilization of the light flux. Another condition which frequently makes a modification of the symmetrical arrangement of units desirable is the presence of machinery, benches, etc., along the wall, necessitating the placing of the outside rows of units sufficiently close to the wall to avoid shadows from the operators and from machinery or materials. Where such benches or machinery are employed much of the time, this arrangement is usually found preferable to the alternative of supplying supplementary lighting units over the benches.

Exterior Lighting for Industrial Plants

Exterior lighting of industrial properties is required principally for the following purposes:

1. The illumination of yard thoroughfares, approaches and passageways;
2. The identification and handling of materials stored out-of-doors;
3. The protection of buildings and materials against incendiarism, explosion, sabotage and theft;
4. The guarding of the plant boundaries to prevent the entrance of unauthorized persons.

Safety demands that any area which an employee is required to traverse after dark be lighted adequately. Owing to insufficient attention to these spaces in the past, the accident toll has been exceedingly high as compared with other parts of the plant used for corresponding periods. The requirements are more severe than in the usual street lighting, inasmuch as in emerging from a brightly lighted building or passing to another the eye does not quickly accommodate itself to function readily under the greatly diminished intensity.

To facilitate the handling of material in a yard with safety and expedition, the matter of shadows must receive careful attention; where material is stored in high piles, satisfactory lighting becomes difficult. The illuminants should, therefore, be mounted high or a number employed to light a given space from several directions. When night work is carried on regularly in the yard over a considerable period, the intensity of illumination should be as high as for similar operations in interiors. Where the light is required only occasionally, a lower standard will suffice.

The electrical energy required with modern incandescent lamp equipments for general illumination of yards is of the order of 0.02 to 0.1 watt per square foot.

Types of equipment which find application in exterior lighting about an industrial plant are the following:

Dome-type enameled-steel reflectors;
Radially-fluted type enameled-steel reflectors;
Prismatic refractor fixtures;
Angle-type enameled-steel reflectors;
Floodlighting projectors.

In selecting any of the equipments for outdoor service, one should be careful to secure well-constructed, weather-proof fixtures.

The dome-type reflectors are suited for use on brackets or mast-arms attached to buildings or poles distributed through the yard. Except in the case of units of 100 watts or less, which may be installed as low as 15 feet above the ground, the mounting height should be not less than 18 feet. Higher suspension will further improve conditions for vision. A degree of uniformity satisfactory for general yard or roadway illumination will be secured if the spacing between the dome units does not exceed four times their mounting height.

Because of the wide distribution from the dome radially-fluted reflector, such units may be mounted at spacings up to six times the height of the lamps above the ground. The lamp filament is, of course, not shielded from the eye with these reflectors and it is, therefore, particularly important that even the small sizes of lamps be mounted not less than 15 feet above the ground, and that the height of sizes above 100 watts be 20 feet or more. Radially-fluted reflectors are available without the central dome part; their use in this form is not to be recommended, however, because the lamp filament must necessarily be placed at a considerably greater distance below the fluted reflecting surface, and the light, therefore, less effectively redirected. The dome radially-fluted units are, in general, also to be preferred to the flat-cone or concentrically-fluted reflectors.

The prismatic refractor fixture as used in street lighting gives the widest distribution of light of any of the equipments for exterior use, and at the same time protects the eye from glare better than does the radial wave unit. The angle at which the maximum candlepower is directed depends upon the position of the filament and hence of the fixture socket with reference to the refractor. For yards, the fixtures should be ordered with the socket in a position such that the maximum candlepower will be delivered at least 15 degrees below the horizontal. The intensity near the horizontal is then greatly reduced and the resulting glare is not excessive. Refractor units should be mounted 20 feet or more above the ground and spaced not more than eight times their height. Typical fixtures deliver from 60 to 70 per cent of the light below the horizontal. They are available in a variety of substantial forms.

The angle-type of enameled-steel reflector may sometimes be used with advantage for spaces between buildings too wide to be lighted adequately from dome reflectors on brackets at the structures, or for open spaces before buildings where it is necessary to avoid setting poles. Such units should, in general, be mounted 25 feet or more above the ground, and the spacing between units on a building face should be within two to three times their mounting height. Angle reflectors deliver from 60 to 65 per cent of the light from the lamp below the horizontal.

The four types of equipment discussed above must be distributed at moderate spacings on supports relatively near the area to be illuminated. This distribution of units results in the marked advantage that at a given point light is usually received from several lamps and from different angles, thus obviating dangerous shadows and minimizing the effect of the outage of an individual lamp. The equipments are efficient and their cost is relatively low. To mount the fixtures, however, it is sometimes necessary to erect additional poles or other supports and to extend the lighting circuits.

With flood-lighting projectors, on the other hand, the light is confined within relatively narrow angles. The resulting beams are of high candlepower, ranging from 5000 to 300,000, and the light may be projected to a given area at a distance. Equipments may be mounted at a few favorable points, often on existing circuits. Thus the cost of additional poles and wiring may sometimes be saved, but this advantage is usually more than offset by the relatively high cost of the projectors themselves and the somewhat lower utilization of light flux. Floodlamps are particularly valuable for providing light quickly in an emergency, for supplementing regular systems and temporarily reinforcing

the intensity at certain points. They fill a great need in illuminating construction work and other locations in or near which no wiring can be carried or no supports placed for the other types of lighting fixtures.

For general application about an industrial plant, units of medium beam spread, from 15 to 30 degrees, are most often suitable. The desirable beam spread under given conditions obviously depends upon the area to be illuminated and the distance of the projector from this surface. Flood-lighting from one direction only should, if possible, be avoided when there are any materials or obstructions to cast shadows, for these will of necessity be long, sharp and dark. However, if flood-lighting lamps can be mounted on two or more sides of a space, excellent illumination will frequently result. In general, the units should be mounted on buildings, platforms or bracket arms at least 30 feet above the ground. A mounting height of 40, 50 or even 60 feet is usually much to be preferred. High-candlepower narrow-angle flood-lamps on building roofs or elevated platforms are valuable in lighting long approaches to a plant or in sweeping open fields and waterfronts about a property.

Power circuits in industrial plants are often of the 230-volt class for greatest economy. This voltage is, however, much less efficient for lighting than is service of the 115-volt class. The light output with the lower voltage is, in the case of incandescent lamps, from 15 to 20 per cent greater for a given wattage and the cost of the lamps is materially less. It will be found, moreover, that the service rendered by the higher voltage sources is somewhat inferior. However, it is not in general desirable to burn two lamps in series. The failure of one of them involves the outage of both; an old and a new lamp will not be found to give satisfactory performance when operated in series. In practically all cases it will be found more economical to install balancer coils or extra transformers if the service be alternating current, or a motor-generator balancer set if the service be direct current, in order to obtain the lower lighting voltage. In all cases the lighting circuits should be separate from the power circuits, both because of the greater voltage fluctuation on the latter and the undesirability of having the lighting system out when troubles occur on the power lines.

COLLATERAL READING

See end of Chapter XII

CHAPTER XII

SIGN AND DISPLAY LIGHTING

[H. H. MAGDSICK]

An illuminated sign, like any other form of advertising, must have two characteristics: *First*, attracting power, or the ability to gain attention; *second*, selling power, or the ability to impress a message and make it endure. In the majority of displays, a third essential is legibility, or the property of showing word or picture in well-defined, clean-cut lines.

Brightness and motion are two of the major characteristics of sign lighting by which the designer obtains attracting and selling power. Originality, beauty and color are tools which the designer uses according to his ability and the extent of the funds available. The picture, border, size and position of the sign are factors which bear tremendously on the effectiveness of the display.

The principal forms of illuminated advertising are:

1. Electric Signs:
   a. Exposed-light Construction, *b.* Enclosed-light Construction.
2. Illuminated Boards:
   a. Bulletins, *b.* Posters.
3. Building Displays:
   a. Exposed Lights, *b.* Enclosed Lights, *c.* Flood Lights.
4. Carnival Lighting.
5. Indoor Signs.

Exposed-light Signs. — At the present time incandescent lamps of all sizes from 10 to 150 watts are used for exposed-lamp displays. The proper lamp in any display depends upon the following factors: The shortest distance from the sign to the people to whom it is to make its appeal; the circulation, or the number of people who pass through the sphere of influence of the sign; and the surroundings and competing brightness. Brightly lighted districts require brighter signs.

These relationships are shown in Table L.

The pattern of an exposed-light display is made up of individual spots of light which correspond to the various incandescent filaments or jets of gaslight. For careful design, and especially when the pattern

TABLE L

Selection of the Proper Incandescent Electric Lamp for Sign and Display Lighting

	For Districts of High Circulation							
	Surrounding Illumination							
	Dark			Medium			Bright	
Small exposed-lamp signs, 25 ft. or less from ground	10-watt clear bulb	25-watt diffusing bulb	50-watt diffusing bulb	50-watt white bulb				
Exposed-lamp signs 25 to 75 ft. from ground	10-watt clear bulb	25-watt diffusing bulb	25-watt blue sign bulb	25-watt clear bulb	50-watt daylight bulb	50-watt clear bulb		
Large or roof exposed-lamp signs, 75 ft. or higher	10-watt clear bulb	25-watt blue sign bulb	25-watt clear bulb	50-watt daylight bulb	50-watt clear bulb	75-watt daylight bulb	75-watt clear bulb	
Enclosed-lamp signs	25-watt blue sign bulb	25-watt clear bulb	50-watt daylight bulb	50-watt clear bulb	75-watt daylight bulb	75-watt clear bulb		
Marquees	25-watt diffusing bulb	50-watt diffusing bulb	50-watt white bulb	75-watt white bulb				
Building-outline lighting	25-watt diffusing bulb	25-watt blue sign bulb	25-watt clear bulb	50-watt diffusing bulb	50-watt blue sign bulb	50-watt daylight bulb	50-watt white bulb	75-watt white, bulb
	For Districts of Low Circulation							
Small exposed-lamp signs, 25 ft. or less from ground	5-watt clear bulb	10-watt clear bulb	25-watt diffusing bulb					
Exposed-lamp signs 25 to 75 ft. from ground	5-watt clear bulb	10-watt clear bulb	25-watt diffusing bulb	25-watt blue sign bulb	25-watt clear bulb			
Large or roof exposed-lamp signs, 75 ft. or higher	10-watt clear bulb	25-watt blue sign bulb	25-watt clear bulb	50-watt daylight bulb	50-watt clear bulb			
Enclosed-lamp signs	25-watt blue sign bulb	25-watt clear bulb	50-watt daylight bulb	50-watt clear bulb				
Marquees	25-watt diffusing bulb	50-watt diffusing bulb	50-watt white bulb					
Building-outline lighting	10-watt clear bulb	25-watt diffusing bulb	25-watt blue sign bulb	25-watt clear bulb	50-watt diffusing bulb			

includes a picture or any departure from rectilinear letters, it is essential that the designer know the size of the spots of light. The size of a spot of light from an exposed light source of any kind depends principally upon the candlepower in the direction of the observer, the distance to the observer, and the total light in the field of vision and the concentration of light near the lamp under observation, called background brightness.

This relationship in the form of an equation is as follows:

$$S = \frac{D}{AB + 0.0083\,D} + 0.0035\,D$$

in which S is the diameter of the spot of light in inches, D is the distance

TABLE LI

BACKGROUND BRIGHTNESS FACTORS (AB)

Lamp size, watts, clear coil filament	Size of sign, total lamps	Values of $A \times B$ — When the general surrounding illumination is: Dark	Medium	Bright
10	100	125	260	400
	500	175	340	500
	1000	225	410	600
	2000	275	490	700
15	100	110	230	350
	500	160	310	450
	1000	210	380	550
	2000	250	450	650
25	100	90	210	325
	500	140	280	420
	1000	175	340	510
	2000	225	420	600
50	100	70	170	275
	500	115	230	350
	1000	160	290	425
	2000	200	350	500
75	100	60	140	225
	500	90	190	285
	1000	120	230	345
	2000	150	280	400
100	100	50	125	200
	500	75	160	250
	1000	100	200	300
	2000	125	240	350

in feet from the lamp to the observer, A and B are constants which depend upon the candlepower of the light source in the direction of the observer and upon all other light in the field of vision and its angular relationship to the light under observation.

Although the factors which make up the constants, A and B, may be determined experimentally, for practical purposes it is sufficiently exact to take these as determined for specific installations as indicated in Table LI.

The values of S may be determined from the equation or more readily from Table LII.

TABLE LII

VALUES OF APPARENT "SPOT OF LIGHT" DIAMETERS "S" IN INCHES

D = Distance in feet	$AB = 50$	$AB = 100$	$AB = 200$	$AB = 300$	$AB = 400$	$AB = 500$	$AB = 600$	$AB = 700$
200	4.6	2.7	1.7	1.4	1.2	1.1	1.0	0.99
400	8.9	5.3	3.4	2.7	2.4	2.2	2.1	2.0
600	13.1	7.8	5.0	4.1	3.6	3.3	3.1	3.0
800	17.0	10.1	6.7	5.6	4.8	4.4	4.1	3.9
1,000	20.7	13.0	8.3	6.8	6.0	5.5	5.2	4.9
2,000	37.0	24.0	16.0	13.0	12.0	11.0	10.0	9.8
5,000	72.0	53.0	38.0	32.0	28.0	27.0	25.0	24.0
10,000	110.0	90.0	70.0	61.0	56.0	52.0	50.0	48.0
20,000	163.0	145.0	125.0	113.0	106.0	100.0	96.0	93.0

In laying out a pattern in which exposed light sources are used, the designer must know first what the width of the stroke or line of light is going to be. This, being made up of the individual spots of light, is equal in width to the diameter of the spots. If he is designing for legibility or clearness of pattern at a given distance, he may determine his stroke width from the table. The distance which he uses is the maximum distance at which the display must be effective. In order that the appearance may be equally satisfactory at the shortest distance at which the display is ordinarily observed, it is necessary for the designer to keep the distance between lamps sufficiently small to make the line of light at this minimum distance continuous or approximately so. The lamp spacing should, therefore, be made equal to, or not much greater than, the spot diameter as calculated for the shorter distance.

When the pattern consists of rectilinear letters, it is not necessary for the designer to lay it out in spots, and a modification of the spot-size equation may be used for this purpose as follows:

$$H = 3\,W + \frac{2\,D_m}{AB + 0.0083\,D_m} + 0.014\,D_m$$

in which H is the height in inches measured on the center lines of the outside rows of lamps as shown in Fig. 122, W is the width of the letter stroke in inches, also measured on the center lines of the outside rows of lamps, and in the case of a single line of lamps is equal to zero; D_m is the greatest distance at which the letter E must be legible; A and B are lamp and background constants and may be taken from Table LI; R is equal to a separation which, at the distance D_m subtends an

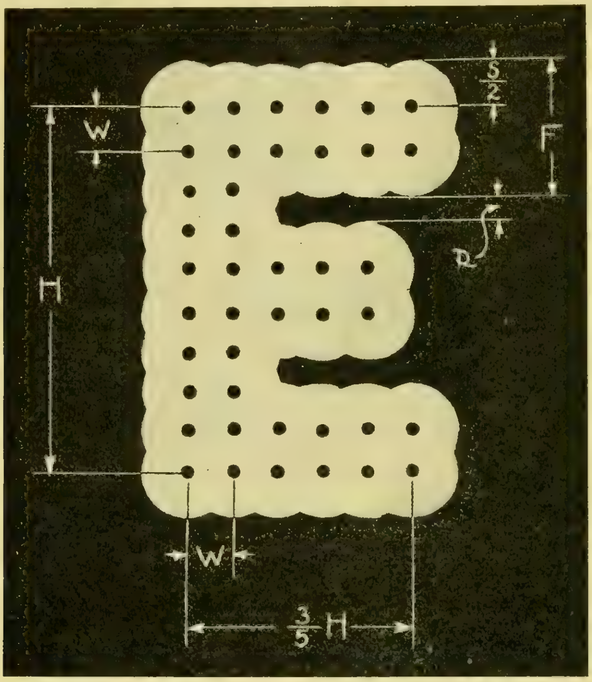


FIG. 122. The legibility equation is based upon a rectilinear letter "E," whose dimensions are as shown. When a single line of lamps is used, $W = 0$.

angle of one minute of arc at the observer's eye, the shortest distance of separation between two objects which can be seen by an average eye.

The relative legibility of other rectilinear letters of the same general proportions is shown in Table LIII. The required dimensions for any letter which is to be legible at a specific distance are, of course, equal to H as found in the equation divided by the relative legibility factor for the specific letter.

TABLE LIII

RELATIVE LEGIBILITY OF LETTERS

A	1.30	*H*	0.92	*O*	1.06	*V*	1.08
B	0.85	*I*	1.41	*P*	1.04	*W*	1.13
C	1.07	*J*	1.21	*Q*	1.06	*X*	1.08
D	1.03	*K*	1.06	*R*	0.97	*Y*	1.04
E	1.00	*L*	1.19	*S*	0.95	*Z*	1.01
F	1.04	*M*	1.13	*T*	1.15		
G	0.92	*N*	1.00	*U*	1.07		

For easy legibility, the dimensions for all letters should be made twice the size determined by the equation and table for the letter which is most difficult to read. This is, of course, the letter with the smallest legibility factor.

Light Motion in Exposed Signs. — Motion is one of the most effective tools the designer can use in planning a display. Four principal forms of motion are widely employed: Flashing, dimming, running or traveling motions, and picture motions (motions which imitate the movement of actual objects).

In exposed electric lamp signs, practically all motion is obtained by connecting and disconnecting lamps in rapid sequence. In order to effect the rapid change of connections " flashers " are used. These are either motor-driven or are thermostatic.

Thermostatic flashers are usually made for one or two lamps only and are, therefore, used chiefly for indoor and very small signs. For all ordinary outdoor display flashing, the motor-driven, rotating-segment type of flasher is used. When more than 15 amperes must be broken, the rotating segment and brush control an extra circuit, which in its turn controls a magnetic breaker for the heavy current.

To obtain the effect of a running border or a traveling motion, the entire pattern is burned continuously with every third or fourth lamp out. The pattern is in light, and the motion consists of series of black spots or gaps which move along the path of light. The effect of direction is lost if every other lamp is burned and the pattern itself is lost if all except the traveling parts are left dark.

In gas signs, which consist of piping in which a series of holes has been drilled for small jets of gas flame, the wind repeatedly blows sections of the sign out. The extinguished lights are immediately ignited again by other sections or by the protected pilot light, and this causes irregular running motions which are quite distinctive.

For picture motions there are three essentials, of which the first is clearness or legibility in each separate view. This may be assured by

designing these views as separate signs. Second, a sufficient number of views must be included to define the entire action. Third, the correct time relation must be given each of the various views. If the picture shows a swing, five views are probably necessary and the law of the pendulum should be used for locating the positions at equal intervals of time. If the picture shows a fountain or sky rocket, the position of the lamps should be properly spaced for equal intervals of time according to the laws of falling bodies.

Enclosed-lamp Signs. — It is not possible to space exposed lamps closely enough to form a continuous line of light at the shortest distance at which small signs are seen. Therefore, in order to avoid the spotted appearance of such signs, many advertisers prefer the smoother though less bright effect obtained with translucent glass letters illuminated from a hidden light source. A 6-inch spacing from lamp to lamp and a 3-inch spacing from lamp to projected edge of pattern will prove satisfactory in signs of ordinary construction, provided the interior surfaces are finished in white.

Bulletin and Poster Boards. — A sharp distinction is drawn between bulletin and poster boards. Bulletin boards are those on which the pattern is painted. These range in size from a few inches to a hundred feet or more. Poster boards are those upon which lithographed posters of a standard 25- by 10-foot size are pasted. Poster advertising has become so highly organized that it is possible to treat it as a single, unvarying example of standardized practice in so far as illumination goes.

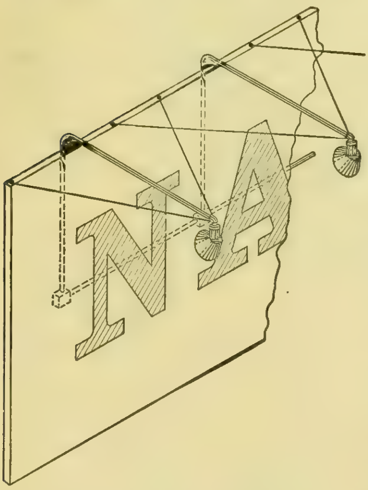


Fig. 123. Simple Method of Installing Porcelain Enameled Angle Reflectors.

For satisfactory illumination of either bulletin or poster boards, the following conditions must obtain: The board must be illuminated to an intensity sufficient to make it stand out strongly in contrast with other objects in the same field of vision; it must be illuminated uniformly — a certain definite variation in illumination must not be exceeded; there should be, if possible, no glare spots; the lighting units should be as inconspicuous as possible.

There are two principal methods of illumination of bulletin andposter boards. In one method the lighting units, usually employing porcelain-enameled angle reflectors, are

mounted above and in front of the display at the end of conduit arms, as indicated in Fig. 123. In the other, the light may be projected from

TABLE LIV

Specifications for Billboard Illumination by Electric Incandescent Lamps

Height of Board, Feet	Mounting Spacing, Feet	Dimensions of Distance Out, Feet	Lighting Units Distance Above Feet	Size of Lamp, Watts	Average Illumination, Foot-candles
3–5	5	4	1	50– 75– 100	5– 9–13
6–8	6	5	1	75–100– 150	6– 9–15
9–12	6½	7	1	150–200– 300	7–10–16
13–17	9	8	1½	200–300– 500	7–11–20
18–21	12	11	2	300–500– 750	6–10–16
22–25	16	15	2	500–750–1000	7–11–16
25	20	18	2	750–1000	7–10

TABLE LV

Standard Poster Illumination by Electric Incandescent Lamps

Recommended lamp sizes for the illumination of standard poster boards (11 × 25 ft.) using three reflectors spaced 5 feet out from top of board and 7 feet apart.

		For Districts of High Circulation	For Districts of Low Circulation
Surrounding or Competing Illumination	Dark	150-watt gas-filled lamp	100-watt gas-filled lamp
	Medium	200-watt gas-filled lamp 300-watt gas-filled lamp	150-watt gas-filled lamp
	Bright	500-watt gas-filled lamp	200-watt gas-filled lamp

When daylight lamps are used, the next larger size is recommended.

For posters which are exceptionally dark and in which the contrasts in the pattern are not pronounced, a lamp of the next larger size is recommended.

In exceptionally dark places, as, for example, along suburban or rural unlighted highways, the next smaller lamp is recommended.

flood-light projectors, usually from below and at one or both sides of the display.

The desirable average intensity for either method is indicated in Tables LIV and LV.

Sign Maintenance. — In general, better advertising value, over a period of a year or more, will be obtained from a small sign which is washed and cleaned just as often as the show window is washed, and which is painted and has a change of lamps three or four times a year, than will be obtained from a sign which is twice as large but which is eglected until it is dirty and 5 or 10 per cent of the lamps are burned out.

Building Displays

Exposed lighting, enclosed lighting and flood-lighting are all used for building displays. The form best suited to, and most desirable for, a particular building depends chiefly upon the following factors: whether the display is planned for a building which is to be erected or a building which is already completed; the architectural beauty of the building; the desired effect — whether sensational or dignified.

The most desirable display cannot always be installed upon a building which has already been erected. It is best, when possible, to determine the form of display to be used at the time the building plans are being drawn up. With the coöperation of the architect, it can be done at this time in such a way that the lighting effect will be in perfect harmony with the architecture; the greatest possible choice in the type and form of display is available; the lamps may be located so as to make maintenance and cleaning easy and inexpensive, and the daytime appearance can be made as satisfactory as that of night.

Exposed Lamps. — Exposed lamp construction for building displays is used in three forms — cornice lighting, building-front lighting, doorway-arch lighting and marquee lighting. The competing brightness and the circulation at the location determine the brightness requirements. Diffusing-bulb lamps prove more effective than clear-bulb lamps in displays which are seen at short distances. The proper lamp for any specific location is shown in Table L.

Enclosed Lamps. — The requirements for proper illumination of this form of display are the same as those for similar construction in signs. The lamps must be spaced so as to obtain satisfactory evenness of illumination, and there must be light enough to make the panels appear bright as compared with surrounding illumination. Buildings in locations serving a large number of people should have brighter displays than those which are seen by fewer people.

Flood-lighting. — The architecture of the building itself demands

careful consideration. Very excellent effects are obtained by flood-lighting certain buildings, statues, etc. The same treatment in another case may fail dismally. This is often because, in the first instance, there is architectural beauty, which, when illuminated, stands out strikingly against the black night sky, and which is doubly beautiful because of the deep shadows; while, in the second case, the building may have been so plain and formless as to have little attracting power by itself. Flood-lighting illumination in such a case merely emphasizes the plainness. It is also impossible by flood-lighting methods to obtain a brightness great enough to make an entire building stand out sharply and effectively when it is surrounded by a great deal of light or located in a brightly lighted city square. For such situations, the illuminated-panel or exposed-lamp construction is preferable. The enclosed-lamp panel construction is, moreover, a very excellent solution of the problem of building decoration where an exposed-lamp decoration is considered too garish or where high surrounding illumination or the building's lack of architectural beauty makes flood-lighting ineffective. It is, however, practically impossible to add the enclosed-lamp panel decoration to an existing building; it must be built in and made a part of the original construction. The panels may be made of glass, the color and texture of which so nearly matches the building facing as to be unnoticed by day.

The application of flood-lighting is not limited to the display lighting of buildings, monuments, etc. It extends also, in many cases, to industry. The time required for outdoor construction work may be considerably reduced by a flood-lighting system which will permit work to be continued throughout the night; the flood-lighting of railroad yards, docks, wharves and the yards of industrial plants permits night work to be done efficiently and with increased safety. Another application is found in the lighting of traffic intersections to facilitate the movement of vehicles and pedestrians and to promote safety. The illumination of large outdoor spaces devoted to pageants or sports, including bathing beaches, drill grounds and open-air theaters, is being most satisfactorily accomplished by flood-lighting. Bulletin boards and painted signs located high up on water towers or chimneys are examples of the application of flood-lighting to electrical advertising.

The design of a flood-lighting installation is governed by the purpose which the illumination is to accomplish. In the case of a bulletin board or a sign, it should be the aim to provide a uniform illumination over the entire surface of the display. In outdoor construction work, railway and industrial yards, it is of great importance that long, heavy shadows be avoided. In the flood-lighting of buildings and monuments,

uniform, shadowless lighting often defeats the purpose of the installation. Here shadows are essential to relief, and variations in intensity in the direction of the light or in color may be used with great effect to emphasize the important details and to suppress others. Extreme care must be exercised, however, to avoid the formation of shadows which distort the appearance of the structure and produce a grotesque result.

Flood-lighting Equipment. — Since a specularly reflecting surface is necessary in order to direct the light into a relatively narrow beam,

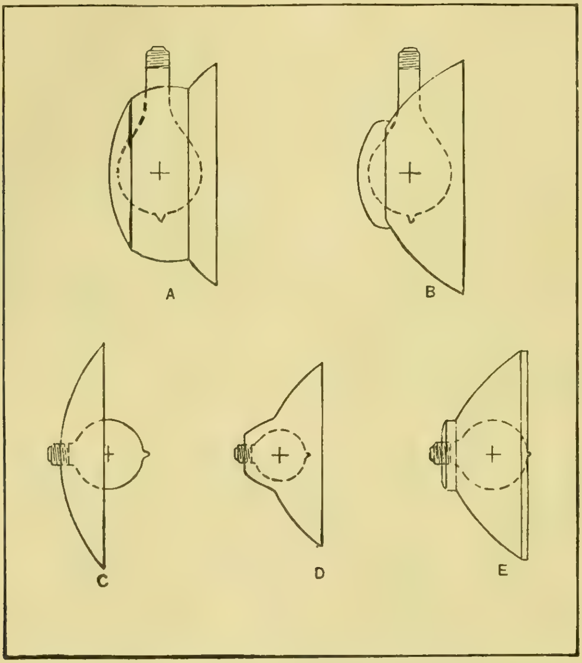


FIG. 124. Typical Floodlighting Reflector Contours.

A and B, for use with ordinary multiple gas-filled tungsten lamps, give moderate and wide spread of beam.

C, D, and E are for use with gas-filled tungsten floodlighting lamps.

C — Shallow parabola, narrow spread of beam.

D, E — Deep reflectors, moderate spread of beam.

such as is desired for flood-lighting, polished metal or mirrored glass reflectors must be employed in such equipments. Because of their high initial reflection-factors and maintenance of efficiency in service, the mirrored glass units have been widely adopted.

The equipments available may be divided into two general classes: those which in various sizes employ 100- to 1000-watt gas-filled tungsten lamps of the regular construction; and those which are designed for

use with flood-lighting lamps, having specially concentrated filaments, of the 250- or 500-watt sizes. The smaller light source of the latter permits more accurate control of the beam.

A factor in design is limitation due to position. With the ordinary multiple-lamp equipments, the minimum spread of beam is about 15 degrees and the maximum about 50 degrees. With a given contour of reflector, some variation in the spread of beam is obtained by moving the lamp filament backward or forward along the axis of the reflector. The maximum spread so obtainable is usually less than twice the minimum angle of divergence.

The percentage of the light from the lamp directed into the beam depends primarily upon the amount intercepted by the reflector and also upon the contour of its surface. The equipments available direct from 20 to 50 per cent of the light into the beam. For all ordinary multiple-lamp equipments, however, and for the flood-lighting lamp projectors of medium and wide beams, an output of 40 to 50 per cent may be obtained with reflectors of proper design. (See Fig. 124.)

Flood-lighting Design Data. — Four factors must be considered in the design of a flood-lighting installation. These are location of equipment, choice of equipment, illumination desired, size and number of units.

Location of Equipment. — In many cases, as in the lighting of monuments, the necessity of locating the lighting units where they will be inconspicuous frequently leaves little choice of position. Advantage may be taken of neighboring buildings or trees, of columns, porches and ledges on the structure itself, and of other possibilities which suggest themselves in each particular problem. Similar locations may be used for the lighting of bulletin boards and painted signs.

In the lighting of yards and outdoor construction work, units may sometimes be located on surrounding buildings, poles or towers; frequently, however, it will be necessary to erect poles especially for the units in order to obtain locations which will allow light to be delivered from sufficiently different angles to destroy dangerous shadows. In order to avoid serious glare from the units, the projectors should be mounted high, at least 30 feet above the ground. Mounting heights of 40, 50 or even 60 feet are usually to be preferred.

Choice of Equipment. — The choice of equipment is largely determined by the dimensions of the area to be lighted and by the location of the equipment with respect to the area. Frequently, two or more forms of equipment can be used advantageously for a single installation.

The beam of light from a projector is conical in form, and hence, when striking a surface perpendicular to its axis, illuminates a circular area. If the beam strikes a surface at an angle, the resultant spot of light is,

of course, elliptical in form. By overlapping the beams, it is possible to obtain an approximately uniform illumination and avoid striations or images of the filament projected by the specularly reflecting surface of the reflector. Ribbed or fluted cover glasses, by which the spread of the beam may be greatly extended in one direction, are now available.

Illumination Desired. — In determining the desirable amount of illumination for the specific installation under consideration, it is necessary to take into account such factors as the color of the surface to be lighted or the nature of the work to be performed, the brightness of surroundings, and, in the case of advertising displays, the attracting power of high illumination. There is seldom danger of overlighting if the installation is properly made. On the other hand, it should be recognized that to make a structure stand out in the midst of bright surroundings, light must be projected in quantity — literally layer upon layer; halfway measures have no place in floodlighting for artistic

TABLE LVI

Foot-candles and Watts per Square Foot Required with Standard Equipment and Under Average Conditions

Subject to be Illuminated	Poorly Illuminated Surroundings		Brightly Illuminated Surroundings	
	Fc.	Watts per Sq. Ft.	Fc.	Watts per Sq. Ft.
Buildings and monuments:				
White or cream	2–4	0.50–1.00	3–6	0.75–1.50
Light yellow and buff	3–6	0.75–1.50	6–12	1.50–3.00
Medium buff	6–12	1.50–3.00	10–20	2.50–5.00
Billboards and painted signs	6–15	1.25–3.75	10–30	2.50–7.50

	Fc.	Watts per Sq. Ft.
Bathing beaches	0.25–2	0.05–0.5
Buildings:		
Construction	2–4	0.5 –1.00
Excavation	0.5–2	0.10–0.50
Docks, wharves and bridges	1–3	0.25–0.75
Drill grounds	0.5–3	0.10–0.75
Outdoor athletics: Football practice, etc	2–6	0.50–1.50
Outdoor stage	2–4	0.50–1.00
Playgrounds	1–3	0.25–0.75
Yards for mills, factories and railroads	0.25–1	0.05–0.25

effect. The ideal subject for floodlighting is a single feature of great beauty in an isolated spot.

Size and Number of Units. — There are two simple methods of determining the size and number of units required. The first, a rough but usually satisfactory method, is based upon successful practice in the past. The values given in Table LVI may be used directly to determine the total number of watts required for any surface under any particular condition. The second method is somewhat more accurate and should be applied where the conditions are unusual. It is based upon the desirable illumination, i.e., the flux-of-light method. For this, the foot-candle values given in Table LVI may be used.

In either method there are several general points to be remembered. A dark object is always extremely difficult to illuminate, regardless of the quantity of light provided. Table LVI shows that light yellow or buff objects require twice the illumination necessary for white objects, while a medium buff requires three times as much. An equally important consideration is the brightness of the surroundings. A building in a poorly lighted section would require only a fraction of the wattage per square foot, to produce the same effect, as an installation in the midst of brightly lighted surroundings.

COLLATERAL READING

Industrial, Sign and Display Lighting

Clewell, C. E., Factory Lighting (McGraw-Hill Co., New York, 1913).

Train Lighting by Electricity (Angus Sinclair Co., New York, 1917).

Ogley, D. H., Works Lighting (Iliffe & Sons, Ltd., London).

Rose, S. L. E., and Butler, H. E., Industrial Lighting, Lighting Journal, **2,** 191, 240 (1914).

Gaster, L., Industrial Lighting, Ill. Eng., **15,** 74 (1922).

Perrot, E. G., and Vogan, F. C., Some Practical Daylight Measurements in Modern Factory Buildings, Trans. I. E. S., **14,** 257 (1919).

Bernhard, F. H., The Lighting of Various Industries, Elec. Rev. (U. S.), **73** (1918).

Home Office Report on Factories and Workshops, Illum. Eng., **15,** 197 (1922).

Gaster, L., Industrial Lighting: Ideal Requirements, Illum. Eng., **15,** 74 (1922).

Harrison, W., and Magdsick, H. H., Exterior Lighting for Industrial Plants, Central Station, **19,** 141 (1919).

Porter, L. C., Simplified Illuminating Engineering Applied to Flood-lighting, Lighting J., **4,** 144 (1916).

Ryan, W. D. A., Illumination of the Panama-Pacific International Exposition, Trans. I. E. S., **11,** 628 (1916)

A Résumé of Floodlighting, Elec. News, **26,** 48 (1917).

Shute, J. M., Problems Involved in Lighting of Signs and Billboards, Elec. Rev. (U. S.), **79,** 581 (1921).

Atherton, C. A., Factors that Determine Sign Legibility, Elec. World, **79,** 1061 (1922).

CHAPTER XIII

STREET LIGHTING

[Ward Harrison]

Difference between Interior Lighting and Street Lighting. — The design of a street-lighting system, at the present time, has little in common with interior-lighting practice. The intensities which here prevail are of a decidedly lower order of magnitude; variations of illumination, on the street surface, in the ratio of 100 to 1, are the general rule; and even the types of lamps used and the methods of supplying them with energy are radically different from those used in interior lighting. The explanation of this situation lies in the fact that in street lighting the areas to be covered are vast and the funds usually considered available for the purpose pitifully small. A single office space of 50 by 100 feet will frequently be supplied with more lamps and a greater wattage than 3 or 4 miles of principal thoroughfare in the same city.

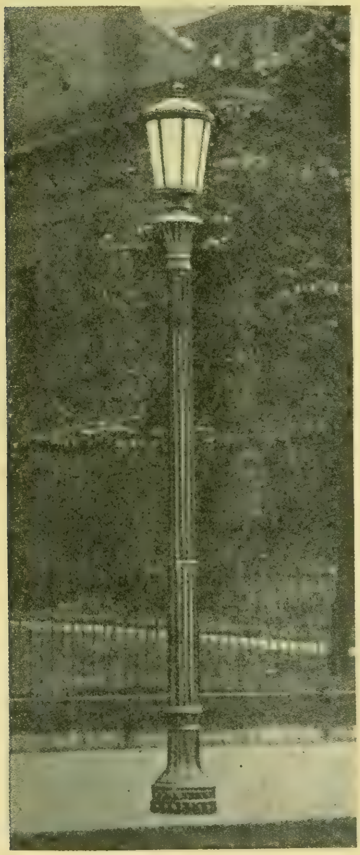


Fig. 125. Lantern-type Unit for Ornamental Lighting.

For many years, then, the task of the street-lighting expert has been principally that of so distributing an insufficient amount of light as to produce the greatest practicable effect. An exception to this rule is found in the best business districts, where high-intensity, or "white-way," lighting is properly considered as an expenditure for advertising to be met either by the city itself or by the local merchants. Ordinarily, however, this high-intensity system covers but a small fraction of the total street mileage of a city.

For ornamental systems, standards should usually be spaced from 65 to 100 feet apart, opposite each other on both sides of the street, and the light source should be at least 12 feet, preferably 15 feet or more, above the pavement. For this service, single-light standards, of which Fig. 125 is an example, are far more efficient than cluster lights, as well as more pleasing in appearance. Either high-candle-power magnetite arc lamps or tungsten lamps may be used.

Requirements for Small Cities and Towns. — Before street lighting can be intelligently planned, it is necessary to have a clear idea of what is to be accomplished by it. While the general objects can be stated in a few words, an analysis of these objects soon leads to a rather complicated situation which can be only briefly reviewed here.

Stated in very general and popular terms, the reasons for lighting streets can be summed up as follows:

1. In all classes of streets, the least that can be expected of the lighting is that it will enable a person to see his way about at night.
2. On some classes of streets the production of an especially well-lighted effect, either on account of congested traffic or because of the ornamental and advertising features, is desired in addition to the first object named.

On a large majority of streets, lighting for purposes of seeing is all that is desired. Even on such streets, however, there will naturally be some difference in the severity of the requirements. The more traffic on a street the greater is the amount of outlay justified for street lighting and the greater is the necessity for safeguarding users of the street from collisions and attack.

Much might be said of the things it is especially necessary to see on a street at night in order to see one's way about, but to mention a few of the principal ones will suffice. For both pedestrians and drivers, irregularities and obstructions of the street surface must be seen. Likewise, other persons using the street must be seen, in order to avoid collision. The value of street lighting in preventing crime is probably about in proportion to the quantity of such lighting. On some very badly lighted streets it is of little value, while on the most brightly lighted downtown streets conditions as to crime prevention are virtually equivalent to daylight.

Technically, the object of street lighting is to produce a certain amount of brightness on street surfaces and upon users of the street. In the daytime there is such a superabundance of light that the distribution of brightness on street surfaces and various objects need not be analyzed very closely; but where the amount of artificial light must be

as meager as it is in a majority of streets in small cities, a much closer analysis is needed.

Distinction between Incident Illumination and Surface Brightness. — The distinction between the illumination incident upon a surface (such as a pavement, sidewalk, tree, vehicle or person) and the surface brightness of such objects must always be kept in mind. It is brightness that is seen; in other words, it is brightness that produces the effect on the eye. The illumination on a surface produces the brightness that is seen, but it does this only by virtue of the light reflected from the surface. That is, the brightness is always proportional to the incident illumination minus the loss by absorption. Since the reflecting power of various surfaces differs greatly, their brightness under a given illumination differs in like proportion.

Between a very new macadam or concrete surface and black mud there may easily be a difference of ten to one in diffuse reflecting power. To produce equal brightness, therefore, the illumination would have to be ten times as great on the black mud as on the light macadam; and the unfortunate thing about this is that there is usually less money available to illuminate the mud than to illuminate the macadam. By daylight, a considerable portion of one's seeing is accomplished by virtue of the different color and reflecting power of various surfaces, although differences in illumination, commonly known as light and shade effects, also have their influence. At night, with street lighting, differences in illumination from different directions, causing light and shade, have a much greater effect.

Silhouette Effect. — The importance of these differences was probably not realized until it was pointed out that a considerable portion of one's seeing on the streets at night is accomplished by virtue of the silhouette effect. That is, one sees many upright objects, such as persons and automobiles, at a distance, not so much by the light reflected from them as by the light background against which they appear as silhouettes. This is especially true in large cities where the background consists almost entirely of pavement, sidewalks and buildings, which are better reflectors and consequently appear brighter than vehicles and persons in dark clothing.

On dirt streets or where oiling has rendered the pavement very dark in color, the effect is not so pronounced. However, even oiled streets, if so well traveled by automobiles as to take on a kind of glint or polish, reflect considerable light by specular reflection as distinct from diffuse reflection. Specular reflection makes these oil-polished street surfaces appear quite bright at certain angles.

If the background is not brighter than the object, the only way to

make the object visible is to illuminate it to such a degree of brightness that it is recognized by contrast with the darker background. Sometimes the same object is seen partly by silhouette and partly by illumination upon it, as in the case where part of the object is seen against a bright background and part against a dark background. The bearing of these silhouette and illumination effects on the spacing and equipment of street lamps will be discussed later.

Road obstructions, such as stones and bricks, for example, may be seen either by illumination or silhouette, but are usually recognized fully as much by the shadows they cast as by any reflection from their own surfaces. Holes and depressions in sidewalks and pavements are usually also recognized by shadows, except when close under a street lamp.

Effect of Shadows. — Some elaborate experiments have been made to determine the merits of various spacings and mounting heights for street lamps and of various types of light distribution from the lamp. Considerable attention has been given to tests in which a number of observers were required to locate obstructions or targets placed in the street, as they walked or drove along. The principal result of this investigation has been to show that obstructions, such as stones in the street, can be better seen with lamps so spaced as to give some shadows behind these obstructions than with the lamps placed at such frequent intervals and so equipped as to produce a more uniform illumination with less pronounced shadows. In all of these experiments, however, the lamp spacing was relatively short as compared with common practice in smaller cities. As uniformity of illumination is high in first cost on account of the large number of lamps and lamp supports required per mile of street, there is no great danger that streets will be lighted too uniformly for best results in the smaller cities.

"Seeing by glint effect" is a term used among engineers to apply to effects obtained when surfaces are wet or when they are highly polished so that there is specular reflection from small portions of them. On rainy nights, glint from the wet sidewalks and pavements takes the place of the partially diffuse reflection ordinarily received. Many images are then seen of the street lamp reflected from the wet pavement and pools of water. Glint is also especially useful in locating mud-puddles with the aid of rather distant street lamps.

In connection with seeing by silhouette, the value of this effect is in many cases greatly increased by the fact that there is just enough glint or specular reflection from the paving or sidewalk for the illumination at points midway between street lamps to produce much greater brightness in the direction of the eye than if the whole of the street were a purely diffuse reflecting surface.

Referring to the diagram of Fig. 126, f is a street lamp 10 feet above the ground and g is the eye of an observer. What is the brightness of the street surface at points a and c to the observer? It will be assumed first that the street surface is a new, white, dusty macadam which approaches a diffuse reflector in its characteristics. Now, a diffuse reflector will appear equally bright from all directions, no matter from what direction it is illuminated. Consequently, the brightness at various points along the street will always be directly proportional to the illumination. Thus, at point a, if the lamp is of 100 candlepower, the illumination will be 100 candlepower divided by 100 (the square of the distance), or 1 foot-candle. At point c, assuming that the lamp emits 100 candlepower in that direction also, and that the distance, f, to c is 100 feet, the illumination on the street surface at c will be, by the same process of figuring, 0.01 foot-candles multiplied by the cosine of the angle i, thus making the actual horizontal illumination at c 0.01 foot-candles multiplied by 0.1, or 0.001 foot-candles. The illumination and brightness would, therefore, be in the ratio of 1

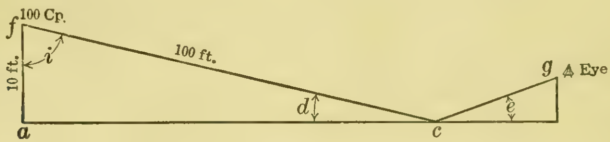


FIG. 126. Street-surface Brightness.

at the point a to 0.001 at the point c. Evidently, with an object between the eye and point c as a background, there could be very little silhouette effect, while between the eye and point a there would be considerable.

If, however, the street surface is glossed with oil or moisture, the character of reflection from it is entirely changed. Instead of appearing equally bright in all directions about any given illuminated spot, it will appear very much brighter when viewed from an angle equal to the angle of incident light. Consider the light which falls on point c from the lamp at f and is reflected to the eye at g. If angles d and e were equal, and if point c were a mirror, the brightness entering the eye from point c would be practically the brightness of the source of light at f. If the point c is a piece of glossy, oiled street surface, it will not behave exactly like a mirror, nor will it act as a diffuse reflector, but its action will be intermediate between the two. It will appear very much brighter when viewed from a direction approximating cg than from other angles. The point a, on the other hand, will appear considerably less bright than if it were a diffuse reflector. This tends to counteract the

enormous difference in illumination falling upon these two points. The practical effect of this, as brought out in various tests, is that, even on an asphalt street which does not have the polish commonly produced by heavy automobile traffic, the brightness varies only in the ratio of 2.7 to 1 with lamps 260 feet apart, while the horizontal illumination varies as 40 to 1. Here again it may be noted that the polishing of a street pavement by heavy traffic of any kind is more conducive to uniformity of brightness, in spite of the non-uniformity of illumination, than are the conditions prevailing in the smaller cities. However, these points must be recognized in all classes of street-lighting problems. It should be remembered in considering the illumination and values cited in Fig. 126 that no allowance is made for any illumination that may be obtained on point *c* from another lamp placed at the back of the observer.

Relative Values of Horizontal and Vertical Illumination. — There has always been considerable discussion in street-lighting circles as to the relative value of vertical as compared with horizontal illumination for street-lighting purposes. It is now generally recognized that both the horizontal illumination on the street surface and the vertical illumination on vertical objects, such as pedestrians and vehicles, must be taken into account. The relative weight given to these two in making up a good street-lighting system will depend very much on the character of the street surface. The importance of the silhouette effect has already been enlarged upon. It is evident that, in producing the silhouette effect, illumination of the street surface is the important thing. However, if the street surface is so dark that it is difficult to get a well-illuminated background, one must fall back upon vertical illumination of objects. It is largely a waste of time to discuss the relative importance of vertical and horizontal illumination, because, with any practicable mounting height of lamps, the illumination midway between lamps giving vertical illumination will be approximately a constant ratio to the horizontal illumination, and no amount of practicable shifting of lamp height and spacing is likely to change this constant enough to have much practical bearing on the subject under discussion.

Lamp Spacing. — It has been shown that variations in intensity of illumination falling on the street surface, from points immediately under lamps to points midway between them, are necessarily very large, even with the most skillful use of appliances for directing the light of the lamp in directions where it is most needed. However, with closer spacing and by figuring in the effect of neighboring lamps, these differences are rapidly reduced. For brightly lighted city streets, a variation of 10 to 1 between lamps at points on the street surface is not likely to be noted. Where lamps are as closely spaced as on business streets,

the question of improving the uniformity of illumination does not offer itself. This applies to the common present-day spacing of ornamental systems, which is from 60 feet to 150 feet. With special care, this distance can be exceeded and still produce satisfactory uniformity, although the ornamental effect may not be what is desired. In outlying streets, where first cost tempts the designer to space lamps at long intervals, the poorly illuminated spaces midway between the lamps come in for first consideration. On such streets, chief interest centers on the points of minimum illumination between lamps. Anything and everything which will bring up this minimum between lamps is desirable if it can be obtained for a reasonable outlay. With a given lamp equipment, the illumination midway between lamps will fall off approximately inversely as the square of the distance. That is, doubling the distance between lamps reduces the minimum illumination to one-fourth. Add to this the fact that the longer the interval between lamps, the less is the amount of brightly lighted background against which things can be seen by silhouette effect, and difficulties are further increased. Lamp spacings of 600 to 1000 feet, which in years past have been so common in smaller cities, are entirely inadequate and inefficient. Furthermore, under modern conditions they are unnecessary from the economy standpoint.

Avoidance of Glare. — The avoidance of glare has long been recognized among experts as desirable in street-lighting practice, because it has been known that the existence of glare from lamps near the line of vision causes a decrease in the seeing ability of the eye — or, in other words, in the visibility of objects — so that, to all practical intents and purposes, more light is required on objects in order to see them clearly than if the source of glare were removed. Quantitative investigations have shown that there is considerable disturbance of vision when a bright lamp is brought within 15 angular degrees of the center line of vision. As the effect of glare increases rapidly as the lamp is brought nearer to the center line of vision, especially within 6 to 8 degrees, there is considerable to be gained in efficiency of illumination, as measured from the ocular standpoint, by hanging the lamp as high, and consequently as far out of the ordinary line of vision, as possible. While no very exact figures can be given, it may be said in a general way that unnecessarily low hanging of lamps may often be the equivalent of throwing away half of the light generated, because of the depressing effect on vision of objects which must be seen past a bright street lamp. The use or non-use of a diffusing globe in a lamp apparently has very little effect on the glare, as the glare effect is dependent upon the candle-power. To be more exact, it depends, according to the best information

obtainable, upon the square root of the candlepower of the lamp used, as emitted in the direction of the eye. The only feasible remedy for street-lighting glare yet evolved is the increase in mounting height of the lamps, and this is well worth while, especially in the range from 10 feet to 15 feet. If the glare effect be taken as 1 at a height of 32 feet, it becomes about 1.9 at a height of 22 feet, about 3 at a height of 16 feet, 4.3 at 15 feet, and 8.4 at 12 feet.

Interference with street lighting by shade trees is a very live subject in the majority of cities, and especially in the smaller cities and towns under consideration. While the majority of such towns have many shade trees, there is considerable difference in the proper method of treatment. In some streets the trees are very large and permit of trimming high to prevent interference with lighting. In other places the trees are of an age at which trimming high enough to prevent interference with the lighting is out of the question. Where the trees are too small to admit of high trimming, center-lamp suspension will usually be necessary to prevent undue shadows. In such a street, no locations can be found, except in the center, which will not involve considerable obstruction of the light by shade trees. On the other hand, where the trees are very large, so that they can be trimmed high to form a high arch over the street, the principal trouble with shadows is not from the boughs and leaves but from the large trunks, which stand in line along the parkway and thus form an effective light barrier for the sidewalk. On such streets the location of lamps in line with one of the rows of tree trunks permits the complete lighting of the roadway and of the sidewalk on the side on which the lamp is located, and causes light to shine through the row of trunks on the opposite side of the street at an angle sufficiently oblique to permit the location of the sidewalk always to be seen. In this way the area of the sidewalk in the shadow is reduced to a minimum.

Importance of the Various Factors. — To sum up, the surface of the street and the sidewalk must receive direct illumination, which, with the resulting shadows, will render irregularities visible. Direct light is also necessary in order to recognize the features of a passer-by, that is, to identify him as a friend or an enemy. Heavy shadows, on the other hand, such as those caused by very thick foliage and tree trunks, tend to reduce the efficiency of the illumination, particularly with respect to safety from attack.

Silhouette effect is the greatest aid in discerning large objects on the road or on the sidewalk. Glint assists in increasing the apparent brilliancy of a specularly reflecting roadway and also reveals puddles on the sidewalk. On the other hand, glare from brilliant lamps tends to

reduce one's ability to see, or, in other words, the effectiveness of illumination.

Analysis of Light Sources. — Because of space restrictions, the only illuminants which will be discussed in connection with street lighting are the gas-filled tungsten lamp and the luminous or magnetic arc lamp. The enclosed carbon arc lamp is now virtually a matter of history, and the flame carbon arc likewise. Magnetite lamps are available in sizes ranging from 300 to 500 watts, approximately 3000 to 9000 lumens, and series incandescent lamps in all sizes from 600 to 10,000 lumens. The question of small units closely spaced versus large units at greater intervals, is one on which there has been almost endless discussion.

Table LVII shows the relative importance of the several factors from the standpoint of the pedestrian, the slow-moving vehicle and the rapidly moving vehicle. The same table also shows the comparative rating of systems of large and small lamps with respect to each of these criteria.

It will be seen that, from the standpoint of the pedestrian and the slow-moving vehicle, those qualities possessed in greatest degree by an installation of small units closely spaced are in most demand, while the requirements of the motorist are more nearly met by the use of powerful light sources at necessarily greater intervals. Residence streets are usually frequented more by pedestrians, and the foliage is likely to be dense on these streets. They should, therefore, be equipped with lamps of small or medium candlepower (250 cp. or less at a spacing of not more than 250 feet and at a height of 15 to 18 feet above the street). On the other hand, for principal thoroughfares, an average spacing distance of 250 to 300 feet should be chosen, and the size of lamp should be the largest that the appropriation will cover, up to perhaps 1000 candlepower.

Equipment. — The most effective type of reflecting equipment for either arc or incandescent lamps in street lighting, especially as regards the large portion of the city outside of the "white-way" district, where questions of economy and efficiency are paramount, has been the subject of much controversy. There are today four types of reflecting equipment in more or less common use for street lighting, and similar results as regards light distribution are obtained from these equipments, whether the arc or an incandescent lamp is used as the light source. These four types are:

1. The flat reflector without diffusing globe;
2. The same with diffusing globe;
3. The prismatic refractor enclosing or partially enclosing light source;

4. The prismatic refractor within a globe of stippled or pebbled glass, which produces a slight breaking up of parallel rays of light without greatly altering their direction.

TABLE LVII

IMPORTANT FACTORS IN STREET ILLUMINATION

(A indicates greatest importance)

Large Units	Small Units	Factor	Pedestrian	Slow-Moving Vehicles	Rapidly-Moving Vehicles
....	Best	Direct Ill.	A	A	C
Best	....	Silhouette	C	B	A
Best	....	Revealing shadow	B	C	B
Good	Good	Glint	D	D	B
Depends on height	Depends on height	Glare	C	A	A
Usually bad	....	Obscuring shadow	B	D	D

The general trend of development in arc lamps has been toward increasing the relative proportion of light flux emitted in zones near the horizontal, and this trend was markedly advanced upon the introduction of the magnetite lamp, in which the arc was held in a fixed position just below a widely distributing reflector. The general argument of those favoring the use of prismatic refractors has been that such accessories make it possible to direct even a greater proportion of the light where it is most needed; by means of a refractor the normal candlepower of the lamp can be more than doubled and thus the intensity can be increased midway between units, at which point the illumination is usually not more than 5 to 10 per cent of the average over the street surface. At the same time the intrinsic brilliancy of the refractor is considerably less than that of an exposed arc, or lamp filament.

On the other hand, the more conservative, who favor the use of the old opal-globe fixtures, contend that with the refractor distribution, much of the light fails to reach the road surface, and is, therefore, wasted; that the glare from such units seriously interferes with vision; that street intersections are inadequately lighted; and, furthermore, that with refractors there is not sufficient light on the portion of the street surface in the immediate vicinity of the lamp to insure that vehicles or pedestrians on other parts of the roadway may be rendered

visible in silhouette against this brighter area. The opal globe is not open, in the same degree, to these objections. It is, however, deficient in revealing smaller obstacles or irregularities in the road surface throughout an extended region midway between lamps. In these darker stretches the pedestrian, as well as the driver of a vehicle, proceeds with difficulty and with a feeling of insecurity.

A disadvantage of every form of street-lighting unit is that in the absence of most rigid inspection and maintenance the efficiency of the system becomes rapidly impaired, owing to the collection of dust and grime.

Street-Lighting Systems. — In the past, street lamps have usually been operated from series circuits, the principal reasons being as follows:

First, the arc lamp is inherently a constant-current device and gives its best operation and greatest efficiency on series rather than on multiple circuits.

Second, the series circuit is the simplest and most efficient method of supplying energy to comparatively small units scattered over wide areas. In many cases electric street lighting antedated the general use of electricity in residences by a considerable period.

Third, a separate system of distribution has furnished the only satisfactory means of automatically lighting and extinguishing street lamps from the central station.

At the present time, when multiple incandescent lamps are available at a very high efficiency, and when a multiple system of distribution is found in almost every locality, there is but one valid reason for the duplication of a distribution system and that is the convenience of turning lamps on and off. If some form of remote-control switch for individual lamps were available and could be utilized simply and inexpensively, the legitimate field of the series circuit would be closely limited. Meanwhile, every effort is being put forth to simplify and reduce the amount of apparatus required for such circuits. Several attempts, with varying success, have been made to eliminate the moving-coil type of transformer or regulator, but as yet no such system has received the full approval of the manufacturers of the lamps with which it must be used. A preferable plan is that of constructing the moving-coil transformer in such a manner that it can be mounted outside on a pole at any convenient location, connected to the 2200-volt power mains, and operated by a time or remote-control switch. Often it is convenient to utilize such transformers for the extension of street-lighting service and to connect directly in series with lamps of the nearest street-lighting circuit the remote-control switches which operate them. Such a plan is especially advantageous in extended systems,

as it often avoids the use of several miles of wire, which would otherwise be required between the nearest lamp of the new circuit and the sub-station.

COLLATERAL READING

Street Lighting

Whipple, F., Municipal Lighting (Detroit, 1889).

Dibdin, W. J., Public Lighting by Gas and Electricity (Sanitary Publishing Co., New York, 1902).

Defrance, Histoire de l'Éclairage des Rues de Paris (Imp. Nationale, Paris, 1904).

Lincoln, E. E., Results of Municipal Electric Lighting in Massachusetts (Houghton, Mifflin Co., New York).

Mackenzie, J. D., Illumination, Electrician, **69**, 16 (1912).

Modern Street Lighting Equipment, Elec. Times, **61**, 490 (1922).

Symposium, Eleven Solutions of a Street Lighting Problem, Trans. I. E. S., **18**, 885 (1923).

Wood, L. A. S., Ornamental Street Lighting, Elec. World, **78**, 1223 (1921).

Butler, H. E., Highway Lighting, Gen. Elec. Rev., **25**, 465 (1922).

Koiner, C. W., Street Lighting Requirements, Elec. World, **80**, 1397 (1922).

Harrison, H. T., Street Lighting Requirements, Ill. Eng., **16**, 6 (1923).

Bettis, A. E., New Practices in Street Lighting, Elec. World, **81**, 321 (1923).

CHAPTER XIV

LIGHT PROJECTION

[H. H. Magdsick]

General Principles

Light projection, as the term is commonly employed, covers the redirection of light flux from artificial sources by means of suitable optical systems, so that it may be utilized within solid angles which are small as compared with those encountered in equipment for general illumination purposes. It was in connection with such applications in a few restricted fields that some of the more important principles of optics and illuminating engineering were long since developed and applied. During recent years these applications have multiplied rapidly, occupying the attention of many illuminating engineers and leading to commercialization on a large scale.

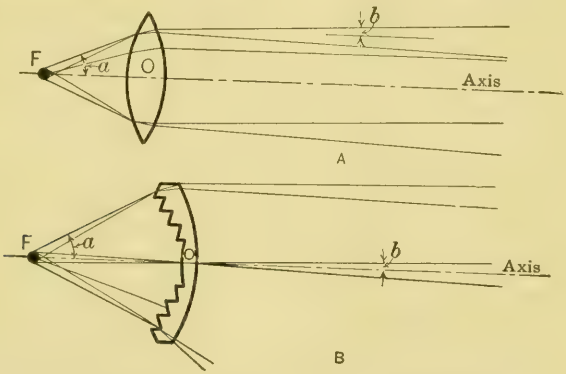


Fig. 127. Light Projection with Lenses.

Two general classes of apparatus are used to direct the flux from a source into the desired small angle: Opaque reflector systems, controlling the light by the principle of specular reflection; and lens systems, depending upon the refractive properties of glass. Frequently, the two forms of control are combined in the same device.

In Fig. 127, *A*, is illustrated the action of a simple convex lens. A light ray emerging from the focus, *F*, is refracted in passing through the lens so as to be projected parallel with the axis, while from an actual source,

as shown, at the focus, a cone of light is projected with an angle of divergence, $2b$, depending upon the size of the source, the focal length of the lens, and the angle, a, at which it is emitted. The greatest angle of divergence is that of the cone issuing at the axis of the lens. These statements apply to lenses intercepting the flux in a relatively small solid angle. As the diameter of a lens increases relative to the focal length, the thickness, and hence the absorption, increase rapidly and the control of the emerging rays is limited by the increasing spherical and chromatic aberration. To reduce these elements of inefficiency, Fresnel, about one hundred years ago, built a lens of concentric rings, Fig. 127, *B*, in effect a large convex lens with sections of the glass removed. He also added concentric prism rings to direct additional light into the beam by total reflection. Later, these prisms were given a curved surface and refraction was combined with reflection to produce the desired results. It will be noted that the sections give rise to a series of dark rings when viewed within the beam, since the light striking the risers is deflected at a large angle from the axis. In Fresnel lenses of reasonably effective angle — the solid angle subtended by the lens at the focus — the contour of the surface may be so corrected as to secure very accurate control of light. They are frequently referred to as stepped, or corrugated, lenses.

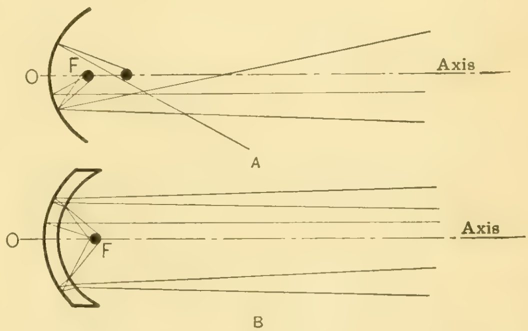


Fig. 128. Light Projection with Opaque Reflectors.

Rays emerging from a source at the center of a sphere are reflected from the polished surface as shown in Fig. 128, *A*. Used in this manner, as an accessory to a lens on the other side of the source, the mirror increases the amount of light intercepted by the lens, provided the source is at least partially transparent. With the source placed on the axis of a spherical mirror at half the radius, rays are returned with only a small divergence from the parallel when the effective angle is not large. Mangin devised a spherical mirror of silvered glass with the radius of the inner surface less than that of the outer, Fig. 128, *B*. The varying degree of refraction introduced by this concavo-convex lens is utilized to keep the divergence of the beam within narrow limits for effective angles up to 120 degrees.

In concentrating light with an opaque reflector, the highest degree of

efficiency and accuracy is secured with a parabolic contour, since all rays from the focus are reflected parallel with the axis no matter how large the effective angle is made. The divergence from a source, as in Fig. 129, *A*, is greatest at the axis and decreases with increasing angles. Only within the angle of the cone showing the smallest divergence, that is, the cone emanating from the edge of the mirror, does the beam contain light from all parts of the surface, and hence only in this region does the measured candlepower obey the inverse square law. Beyond this limiting cone, light is received from a decreasing zone of the reflector, until at the edge of the cone only the point at the axis is effective. Fig. 129, *B*, shows one combination of reflecting surfaces and lens among several that may be employed to meet various requirements.

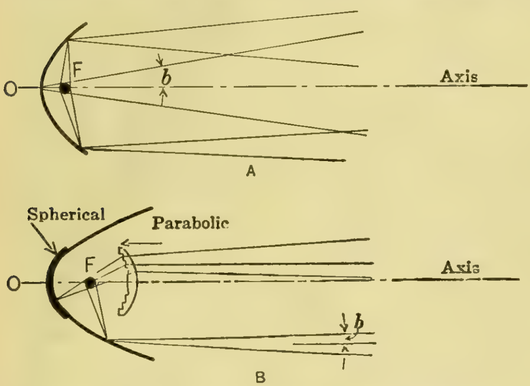


FIG. 129. Light Projection with Opaque Reflectors.

In all of the projection devices described above, a part of the beam receives light from the entire surface. In some cases, this occurs at the axis only; in others, over a wider angle. The brightness of the surface is in every case the brightness of the source at the respective angle multiplied by the coefficient of reflection or transmission of the system. The intensity of the beam within this range is, therefore, the product of the brightness and the projected area of the surface; variations in the focal length and the effective angle do not change the result. The multiplying factor of the system is then approximately the ratio of the squares of the diameter of the mirror and the diameter of the source. Table II, Chap. II, giving the brightness of the various sources, indicates their relative values as far as the production of the maximum beam intensities is concerned.

In most applications, a beam can advantageously be utilized with a divergence so great that the total amount of flux in the beam is of equal or greater importance than the central density. The effective angle of the system, the size of the source, and the focal length are important factors in determining the width of the beam, the total flux, and its distribution.

The average opaque projector system directs from 30 to 60 per cent of the available light into the beam; with lens systems, typical effective

angles are so small that only 5 to 20 per cent is transmitted, although these values are greatly exceeded in lenses used for lighthouses and some other special services. The cost of the respective types of apparatus for different sizes is, of course, often the determining factor in their adoption; in general, the cost of lenses increases more rapidly with larger sizes.

There are four principal kinds of surfaces employed in opaque projectors. Those of mirrored glass and silvered metal have a coefficient of reflection of the order of 85 per cent. Polished aluminum reflects slightly more than 60 per cent of the incident light, and a nickel-plated brass surface has an efficiency of less than 55 per cent. All of the metal surfaces tarnish and require repolishing or replating from time to time. Silvered metal deteriorates rapidly where air circulates over it, particularly in a salt atmosphere and where fumes from stacks are present.

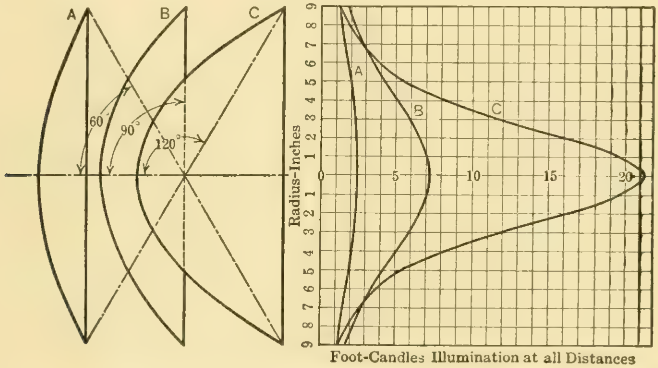


FIG. 130. Parabolic Mirror and Point Source Beam Characteristics.

The nickeled and aluminum surfaces depreciate less rapidly. The aluminum has the further advantage that repolishing does not also in time involve replating as it does with the other metal units. Silvered glass is usually found the most desirable and economical in the long run, although where there is no intense heating and the reflectors may be tightly enclosed, silvered metal is found very satisfactory. The light absorption by lenses varies with the thickness of the glass and the nature of the construction; 10 to 15 per cent may be taken as typical values. With Fresnel lenses there is a further loss due to the rings produced by the risers.

The large proportion of the projection field served by the parabolic reflector makes a further analysis of its properties with different sources desirable. In Fig. 130 are shown the beam characteristics that are approached as the source approaches a point radiating equally in all

directions. The rays are parallel and the apparent candlepower is, of course, different at each distance measured. The density of the flux at any radius is given by the formula:

$$E = \frac{mI}{(F + L)^2}$$

where m = coefficient of reflection of mirror,
E = illumination on a plane normal to the beam,
F = focal length of mirror in inches,
L = distance from focal point to point in beam in feet,
I = candlepower.

The results are shown for three reflectors of equal diameter but of different focal length and effective angle.

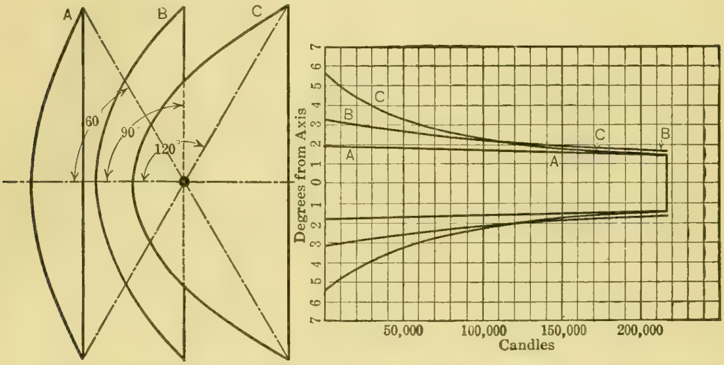


FIG. 131. Parabolic Mirror and Spherical Source Beam Characteristics.

In Fig. 131 a similar analysis is made for a spherical source of 0.5 inch diameter and a brilliancy of 1000 candles per square inch. In this case the equation for the axial density of the beam becomes:

$$E = \frac{4\,\pi m I F^2}{sL^2} \tan^2 \tfrac{1}{2}\, a = \frac{\pi m B R^2}{L^2}$$

where s = area of light source in square centimeters,
B = brightness in candles per square centimeter,
a = angle measured about focus in degrees.

Hence

$$I_b = \pi R^2 B m.$$

The intensity varies, for fixed focal length, with the square of the tangent of one-fourth the effective angle; for fixed angle, as the square of the focal length. Also, the axial intensity is seen to depend upon the brightness of the source but is not affected by its size; it is equal for all parabolic mirrors having the same diameter. The same intensity will be

directed at all angles within which light is received from the entire surface of the reflector. This angular spread is determined by the size of the source and its angular radius viewed from the edge of the reflector. The intensity at other angles is proportional to the area of the mirror contributing light.

These characteristics of the beam apply at distances beyond the point at which the rays from the extreme edge of the reflector cross the axis. This point of maximum density, from which the inverse square law takes effect, is found from the equation

$$L_0 = \frac{R\left(F + \frac{R^2}{4F}\right)}{12\,r}$$

where r = radius of source in inches.

For a disk source the characteristics are given in Fig. 132. Here, again, $IB = R^2Bm$.

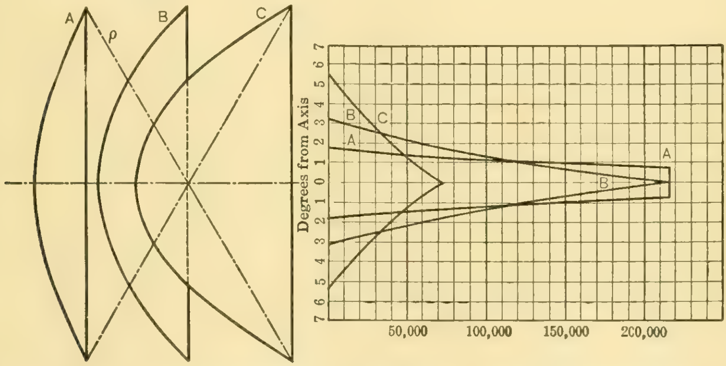


FIG. 132. Parabolic Mirror and Disk Source Beam Characteristics.

With a disk source, a wider angular opening than 180 degrees is not effective, since the projected area becomes zero at 90 degrees from the axis. The effective diameter of reflector C is, therefore, reduced to $2A$. The distance from the focus at which the inverse square region begins is in this case

$$L_0 = \frac{R\left(F + \frac{R^2}{4F}\right)}{12\,r\cos a}.$$

LIGHT SIGNALS

Railway Signals

Optical System. — The lenses ordinarily used in railway signals are of the Fresnel type with the edges of the prismatic rings toward the light source; they are termed " simple optical " lenses in this service.

Sometimes the edges of the prismatic rings are pointed outward; the lenses are then termed inverted lenses and require a cover glass, but have the advantage that none of the light is deflected by the risers of the prisms. The usual diameter of the simple optical lens is $5\frac{3}{8}$ inches, the focal distance being $3\frac{1}{2}$ inches. With the oil flame this lens gives a beam spread of some 15 feet in 100; with the usual electric lamp the spread is about 12 feet in 100.

Color is usually obtained by the use of colored lenses; sometimes, however, as in the case of semaphore "spectacles," a color screen is placed in front of a clear glass lens. Relative effective ranges for commercial colored lenses, as reported by the American Railway Signal Association, are:

Yellow	1.0 to 1.5
Green	2.5 to 3.0
Red	3.0 to 3.5
Clear	8.0 to 12.0

The range for a clear lens in a signal device of the usual type is estimated as from 8 to 12 miles. The visibility is decreased when the field surrounding the lens is slightly illuminated, as in a slight haze, or when other light sources are nearby. The candlepower required for satisfactory signaling varies from a very low value for night service up to a high value when a positive indication is required in bright sunlight. Tests have recently shown that it requires a minimum mean spherical candlepower of 24 behind a standard signal lens for the signal to be seen at 2000 feet with the sun on the horizon in the background.

Light Sources. — Oil has been extensively used as an illuminant, especially in remote localities. A special signal oil is used which does not freeze in cold weather and which has sufficient body to prevent flooding when used in swinging hand-lanterns. Lanterns of fixed signals are operated continuously, being cared for on a regular maintenance schedule. The oil lamp has numerous disadvantages, however: its cost is high, especially in recent years since the price of oil has mounted; incrustation of the wick and deposit of soot on the inner surfaces of the lens cause considerable loss in candlepower (often a 5 to 1 reduction in 100 hours' burning); and the lamp requires frequent attention by the maintenance force.

The incandescent electric lamp has been used for many years where electric power is readily available. Primary batteries of the copper-zinc, caustic-soda type are frequently used as a source of supply where power lines are not readily available. The incandescent lamp has marked advantages over oil as an illuminant, particularly in matters of cost, maintenance and brilliancy of source.

The type of incandescent lamp used depends very largely upon the power available. Where direct-current lighting circuits are the only source at hand, the low-wattage lamp of the 115-volt class is generally employed. Where primary batteries furnish the energy, a low-voltage lamp is used on either 4 or 6 cells of primary battery. If alternating-current power lines are available along the right of way, transformers are employed to supply low-voltage lamps. Where primary batteries are used, the cost of energy is extremely high, sometimes as great as $15 per kilowatt-hour. Hence it is very desirable that lamps used for this service be as efficient as practicable, to reduce operating costs.

Reliability is undoubtedly the most important factor in railway signal lighting. The signal must under no consideration be out when it is supposed to be lighted. Not only is the cost of simply stopping a train a considerable item, but an accident might occur if the signal failed. With electric signal lighting it has, therefore, been customary to employ two lamps, both operating continuously; sometimes a relay arrangement is used which will switch on the second lamp when the first burns out. A more recent development is the two-filament lamp which contains two similar filaments operating in parallel. The possibility that both will fail at the same time is remote. Failure of one filament is readily perceptible to the maintenance force, with the result that the replacement is promptly made. The remaining filament, however, provides sufficient light to render the signal effective until a new lamp can be installed.

Approach Lighting. — Where electric energy is limited or costly, as with primary-battery systems, and on outlying divisions where trains are infrequent, the lamps are not always burned continuously. Relays have been developed which cause the lamp to be lighted only upon the approach of a train and extinguished after the train has passed. This method of control is called "approach lighting" and is widely used.

In some cases valves are employed which turn off the signal when daylight radiation strikes it. These are used principally in switch signal lighting.

Phantom Indications. — Light beams from such sources as automobile headlamps, nearby electric lights, or even the headlamp of the approaching locomotive itself, sometimes enter the signal lens and, being reflected back, give the signal the appearance of being lighted. Such phantom indications have been a frequent source of trouble in some cases. Sometimes the apparent color is quite different from that of the signal lens. Placing a hood over the signal is effective in reducing this difficulty. A cover glass, so designed as to turn aside the light rays incident upon it from outside sources, is also used for this purpose.

Position and Color Light Signals. — The older method of block signaling employed the familiar semaphore arm by day and a light by night. Movements of the semaphore arm covered the light with corresponding color screens for night signaling. The modern method, however, is to utilize lamps for both day and night signals. Several lamps are generally used. In one type of signal the position of the lighted lamps gives the proper indication. Such a signal is entirely electrically controlled through relays and does away with the necessity for the motor and dash-pot apparatus for moving the semaphore. Clear lenses are usually used in this type of signal.

On some roads three lamps with colored lenses — one red, one green, one yellow — are used. Green indicates *clear*; yellow, *slow;* and red, *stop.* A broken lens gives a white signal which indicates *stop.* The normal daylight range of such a signal is some 3000 feet; and under the worst conditions, when opposed to direct sunlight, the range is not less than 2000 feet. In a snow storm, for example, such a signal shows two or three times as far as semaphore arms.

These higher-intensity signals are being adopted in increasing numbers.

Military Signaling

Military searchlight projectors have been used to transmit signals at night for more than 50 miles, by training the beam on a cloud. They are also used in the navy for day signaling over considerable distances, and have the advantage that the narrow beam precludes observation by other vessels, even though only a few degrees removed.

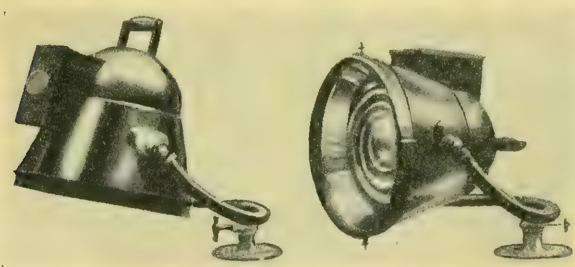


Fig. 133. — Signaling Projector for Aircraft.

Several small incandescent lamps, mounted in the ring focus of a cylindrical Fresnel lens, are used with a Morse key for night signaling in the navy at moderate distances, superseding the Ardois and other devices.

During the war, the land forces made extensive use of low-candlepower metal-filament lamps equipped with paraboloid reflectors. Morse signals are reported to have been read at 11 miles, at the rate of 17 words per minute, with this apparatus. Fig. 133 illustrates a 150-watt signaling projector employed on British aircraft. The properties

of the spherical and parabolic mirrors, as well as those of the dioptric lens, are utilized.

A novel device developed during the war utilized invisible radiation in a narrow region of the spectrum just beyond the violet (0.40 to 0.35μ). A Mangin mirror reflects sufficiently well in this region to permit the use of an ordinary headlight lamp. A special glass filter, to cut off visible radiation, was designed, and an extensive investigation led to the use of a barium-platinum-cyanide fluorescent receiving screen, which fluoresces with a considerable intensity even under weak stimuli. One of the great advantages of this system is the fact that glass is quite transparent to radiation in this part of the spectrum and hence the receiving screen can be used on occasion with an ordinary prism field glass. In practice, two telescopes are fixed side by side; one for sending, containing duplicate lamps, filter, eye-piece and transmitting lens; the other for receiving, containing a condensing lens with the fluorescent screen at its focus, and an eye-piece. The beam received appears in the eye-piece as a little green moon which blinks its signals. The signal is, of course, invisible except to those provided with the proper receiving apparatus.

RAILWAY HEADLIGHTING

Electric Cars

On street cars for ordinary city service, the headlamps need serve only as markers. For suburban and interurban runs, with higher speeds and dark roads, a higher intensity is required, both to serve as a warning at greater distances of the approach of a car or train, and to illuminate objects on the track at a sufficient distance to allow the car to be stopped before reaching them. Figure 134 gives photometric data for several equipments for headlighting, typical of those used in this service. Since high-voltage direct current is available, the magnetite arc has been found to be particularly useful in this field where a high-intensity beam is wanted. The large amount of steadying resistance stabilizes the arc, and when the equipment includes a good lens, good control is secured, with the results shown in Fig. 135.

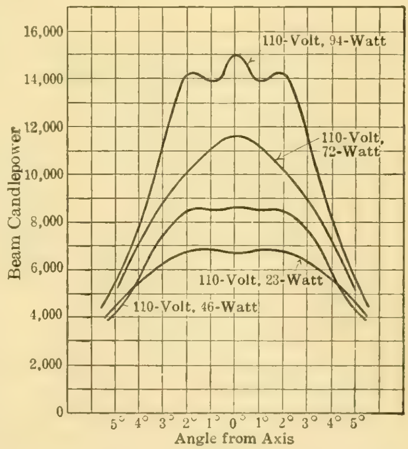


FIG. 134. Beam Candlepowers of Typical Electric Street Railway Head Lamps. Parabolic Reflector of $1\frac{1}{4}$-in. Focus and $8\frac{3}{8}$-in. Diameter.

Steam Locomotives

The Interstate Commerce Commission has issued the following rules relative to locomotive headlighting:

Each locomotive used in road service between sunset and sunrise shall have a headlight which will afford sufficient illumination to enable a person in the cab, who possesses the usual visual capacity required of locomotive enginemen, to see in a clear atmosphere a dark object as large as a man of average size standing erect at a distance of at least 800 feet and in front of such headlight; and such headlight must be maintained in good condition.

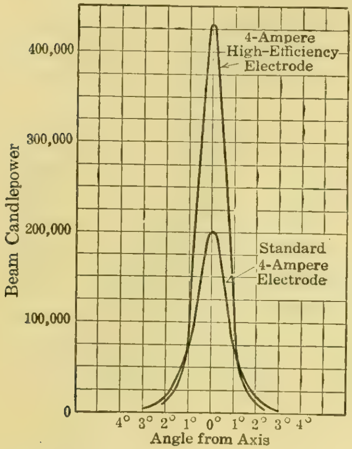


FIG. 135. Beam Candlepower of Luminous Arc Interurban Head Lamps with 12-in. Semaphore Lens.

Such headlight shall be provided with a device whereby the light from same may be diminished in yards, at stations, or when meeting trains.

Sources. — The problem is, therefore, one of securing a beam to meet these requirements. The opaque reflector of paraboloidal contour is readily adaptable to this service. The electric arc and the incandescent lamp are the only types of sources which give sufficient beam candle-power to meet the requirements of the Interstate Commerce Commission. Until the development of the concentrated-filament gas-filled incandescent lamp, the electric arc was used almost exclusively. The concentrated-filament lamp gives a source of high brilliancy and has rapidly replaced the arc lamp with its disadvantages of instability of the arc, difficulty in keeping globe and reflector clean, etc. During the war, the United States Railroad Administration, lacking definite information, arbitrarily ruled that only a headlight equipped with a 250-watt, 32-volt, gas-filled tungsten lamp in an 18-inch silver-plated metal reflector should be used.

Reflectors. — Tests which have been conducted since the war indicate little difference in " pick up " ability between the 12-inch and 18-inch reflectors when they are new and polished. It has been further determined that the 50-watt lamp with a concentrated filament will meet the 800-foot " pick up " requirement if used in a new, highly polished reflector. Higher wattages are generally used, however, to provide an ample factor of safety.

The metal reflectors used in railroad service are ordinarily of silver-plated copper. Some difficulty has been experienced in holding the reflector so that its shape is not distorted. Silver-backed glass reflectors of crystal and uranium glass are being used in increasing numbers. Initially the metal reflector is better than the glass reflector; this advantage, however, is soon overcome, owing to the rapid depreciation from tarnishing of the polished metal surface. The tarnish cuts down the " pick up " distance, but the loss in distance is not so great as is the reduction in light output.

A slight fog has the curious effect of making a dark object in the beam more easily visible. The probable explanation is that the dark object is seen by virtue of the contrast between it and the somewhat brighter fog background. This brighter background is caused by the scattering of light by the particles of water vapor in the air. A dense fog, of course, presents a difficult problem. The scattering of light is so excessive that there is the effect of a white wall or curtain, which the eye of the engineer fails to pierce, just ahead of the locomotive.

Glare. — The glare of an unmodified headlight beam is very disturbing, not only in that it renders signals less noticeable to the driver of a train approaching from the opposite direction, but also in that it hinders the work of the towerman, who must read the classification number on the side of the headlight as the engine speeds past. Some attempts have been made to eliminate this glare by the use of diffusing or redirecting lenses, as in automobile headlight practice. Tests, however, indicate that such methods reduce the " pick up " distance materially. On the other hand, the brightness of the headlamp is reduced and the approaching engineer can better perceive objects up to (but not beyond) the oncoming headlight. The usual custom of today is to dim the headlight by inserting a resistance in series with the lamp when meeting trains, entering terminals, etc.

VEHICLE HEADLIGHTING

Vision. — It is desirable that the driver of an automobile be able to see his way for several hundred feet in advance, and since he must provide his own lamps and direct the light unfavorably for lighting the roadway, it becomes necessary to project a high intensity. If there were but one automobile and a lonely road, the headlighting problem would be simply solved. But the high-intensity equipments employing closely coiled, low-voltage filaments, in solving the problem of lighting the road, introduced a serious problem in that they temporarily blinded the driver or pedestrian who was forced to come within their angle of action.

Investigations to determine the proper and desirable distribution of light from headlamps, taking into account both the needs of the driver and the prevention of glare for the pedestrian and the driver of an oncoming vehicle, have resulted in the development of equipment for securing a desirable type of beam, or one approaching it; and today there are road-lighting equipments, which, if properly adjusted, give good results, for the usual conditions of driving.

Laws. — The various states have passed many laws intended to control automotive headlighting. Apparently, the aim of some of the older rules was to prevent glare rather than to provide satisfactory road lighting. Investigations showed that the desired end — satisfactory road lighting without glare — could be accomplished with much more certainty, and the enforcement of the regulations greatly

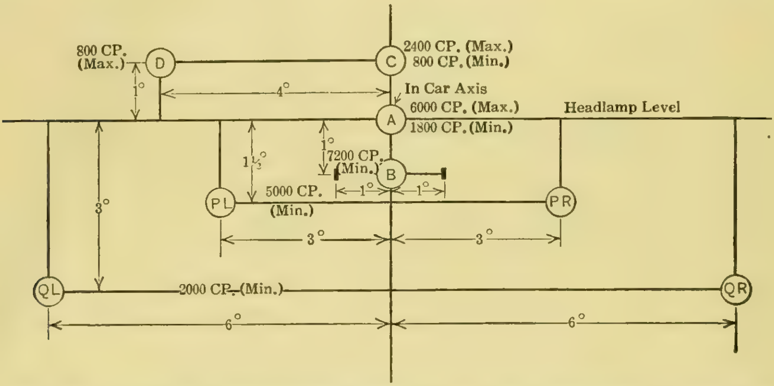


FIG. 136. Limiting Candlepower Values from Two Headlamps. Intensities Measured in Vertical Plane 100 Feet Ahead of the Car.

facilitated, by a definite statement of the maximum candlepower which may be directed in those angles where it interferes with the vision of the approaching driver, and the minimum intensity which must be directed to various parts of the road to insure a satisfactory driving light. The Illuminating Engineering Society and the Society of Automotive Engineers have been sponsors for regulations of this kind in the form shown in Fig. 136. The tendency of new state legislation is toward the adoption of this system. The values of road illumination provided in these specifications represent the minimum considered necessary from the standpoint of safety. A lens or device which will just meet these requirements in a laboratory, and hence will receive state approval, cannot be depended upon to show anywhere near the required values under some service conditions. In the laboratory, selected reflectors, lamps, and cover glasses are employed and the equipment

is operated at rated voltage. In service, owing to conditions beyond the control of the car owner, the voltage of the lamps is often below that required to give full candlepower; furthermore, there are departures from a perfect product in reflectors, cover glasses, incandescent lamps, and sockets and there is some depreciation due to dust as well as to blackening of the lamps. Hence, to insure that the designated values of road illumination will actually be obtained in service, it is necessary that the laboratory test should in general show twice these intensities. This fact has not been sufficiently realized, and there are many cars now equipped with devices which, in a large percentage of the cases, are not satisfactory in service although they have passed the laboratory tests.

Light Distribution. — The purpose of most present-day headlighting equipment is to gather the light from the lamp, direct it down the road

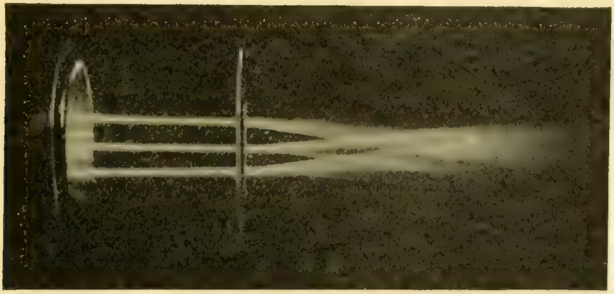


FIG. 137. Spreading Rays of Light by Vertical Flutes in the Cover Glass. Top View.

ahead, spread it into a broad, shallow beam to cover the road surface, and tilt it so that its top is horizontal. The broad, shallow beam covers the road surface and provides driving light; tilting until the top of the beam is horizontal, if the beam has a sharp cut-off at the top, keeps the high-intensity light down upon the road and out of the eyes of an approaching driver. The parabolic reflector serves to gather the light from the lamp. Spreading of the beam may be accomplished by vertical flutes in the cover glass. Figure 137 illustrates the spreading effect of such flutes. Tilting may be accomplished by tilting the headlamp itself; in some devices, bending prisms (Fig. 138) in the cover glass help to perform this function. If bending prisms are used, some parts of the beam can be tilted more than others; in this way greater depth of beam may be secured; this gives additional light near the car, desirable for lighting roadways, ditches, etc. Figure 139 shows the cross-section of the beam from a parabolic reflector with a cover glass

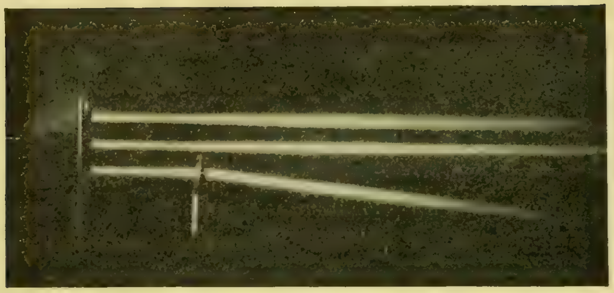


FIG. 138. Bending a Ray of Light with a Horizontal Prism. Side View.

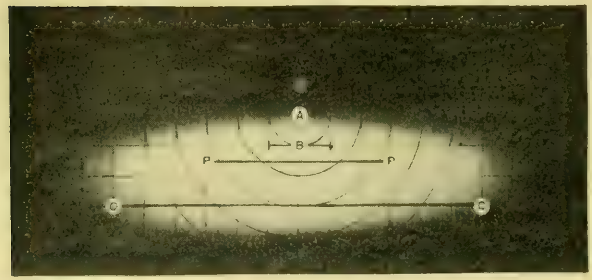


FIG. 139. Cross-Section of Beam from Parabolic Reflector and Cover Glass Having Uniform Spreading Flutes.

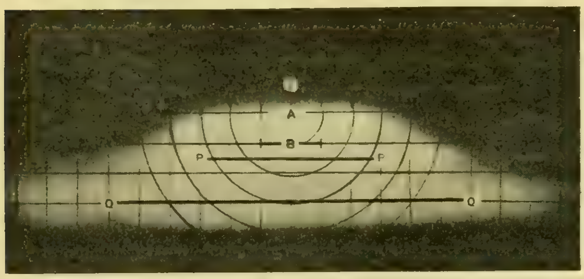


FIG. 140. Cross-Section of More Desirable Beam from Parabolic Reflector and Cover Glass in which the Rays from Different Sections of the Beam are Spread and Bent in Varying Amounts.

having uniform spreading flutes. Figure 140 shows the cross-section of a more desirable beam in which the rays from different sections are bent and spread in varying amounts. A small amount of light is allowed to escape above the horizontal — sufficient to reveal overhanging obstructions but not enough to cause glare. The road ahead and near the car is uniformly well lighted, as are the sides of the road, enabling the driver to proceed with a feeling of safety.

The fluted reflector is a recent development which employs vertical flutes in the reflector itself for spreading the beam. The necessary tilt is secured by tilting the reflector and depth of beam by modification of the contour. No special lens is required, and a clear cover glass is provided as a protection for the mirrored reflector surface.

Substantially all of the headlighting equipments now on the market were designed for use with the 21-candlepower gas-filled incandescent lamp and give best results with this lamp.

Even with the progress that has been made, there is still found a considerable amount of glare upon the highways, due usually either to poor equipment or poor adjustment. Headlamps are extremely sensitive to adjustment. The beam may be compared with a lever with a short arm of some $1\frac{1}{2}$ inches and a long arm of perhaps 100 feet. It is obvious that a small change in the position of the lamp will make a considerable difference in the beam out on the road. An immediate improvement in road-lighting conditions would result if all drivers gave proper attention to this important feature of their cars.

SEARCHLIGHTING

Equipment. — Searchlighting equipments were developed principally in connection with the military service, sixty years ago. During all of the intervening period they have been used as an effective means of defense against night attack, for locating enemy vessels, aircraft, and fortifications, as well as for signaling purposes. Nearly forty years ago, the first accurately ground parabolic mirrors became available, and these with the direct-current carbon arc have been the standard equipment. Few improvements in either the light source or the optical system were made until shortly before the World War, when the increasing range of torpedoes and the menace of aircraft led to rapid and radical developments.

Figure 141 shows a number of small hand-controlled searchlighting equipments such as are used in commercial work and in navigation. The electrodes are in a horizontal position with the positive tip at the focus of the mirror, inasmuch as most of the light is radiated from this

surface. Figure 142, *A*, is a military equipment provided with an automatic control and feeding mechanism. The iris shutter serves to shut off the beam quickly or to keep it covered until full candlepower is obtained. A considerable delay is encountered in reestablishing full intensity after the arc has been extinguished. For rapid signaling, Venetian blinds or louvers are used in front of the cover glass, as shown in Fig. 142, *B*. In field operation, equipments are sometimes mounted on railway cars or on trucks with elevated platforms.

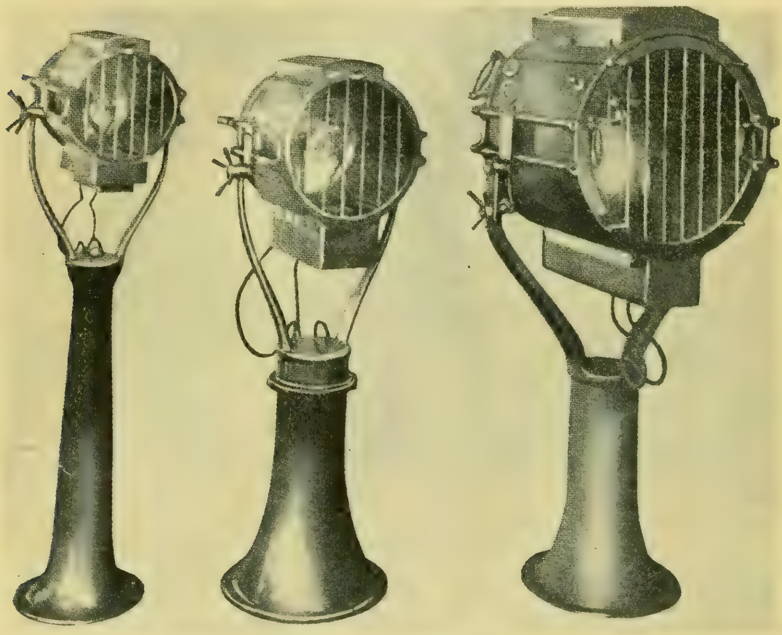
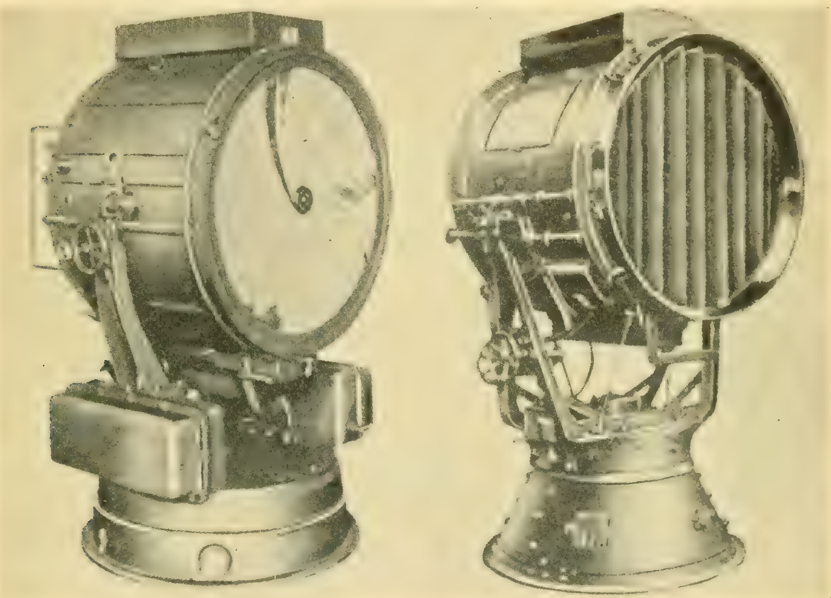


Fig. 141. Hand-controlled Commercial Searchlighting Equipments.

The demand for a more mobile type of searchlight during the World War, particularly for anti-aircraft operations, led to the development of a greatly simplified but powerful unit which can be transported on, and supplied with energy from, a motor car. This 60-inch searchlight weighs only one-tenth as much as the former standard unit of that size. Its cost is only one-third as great and it consists of only about one hundred parts as compared with several thousand for the old designs. It can be produced in one-fourth the time required for the old models and is very much more rugged.

Optical Characteristics. — Optically, searchlights consist of accurately polished parabolic mirrors, except in diameters of 18 inches or

less, for which Mangin mirrors can be made more cheaply. The data for typical carbon arc searchlight projectors are given in Table LVIII. It will be noticed that the focal length of the mirrors is about 40 per cent of the diameter. The included angle is, therefore, about 120 or 130 degrees. Within this angle is included a large percentage of the light emitted by the arc; to increase the angle for a given diameter of mirror would result in decreasing the effectiveness of the beam, for in most applications of searchlighting the interest is only in maintaining a maximum mid-beam intensity. Any considerable divergence of the



A *B*

Fig. 142. Military Searchlighting Equipments.

beam serves actually to interfere with vision of objects illuminated by the middle of the beam. The beam appears to the observer as a bright shaft of light which has the effect of producing a curtain between the observer and the illuminated object; standing at about 500 feet to the side of the searchlight increases the seeing ability of the observer about three times. Remote-control equipment has been developed in order to enable an operator, located at some other place than at the searchlight, to change the beam direction at will. This is of especial advantage in increasing the useful range, as well as from other standpoints in military application.

TABLE LVIII

TYPICAL CARBON ARC SEARCHLIGHTING PROJECTORS

Nominal Diameter of Mirror in Inches	Amperes	Actual Diameter of Mirror in Inches	Focal Length in Inches	Reflector
9	10	....	....	Mangin Mirror
13	20	....	....	Mangin Mirror
18	35	$19\frac{3}{16}$	$7\frac{7}{8}$	Mangin Mirror
24	50	$25\frac{1}{8}$	10	Parabolic Mirror
30	80	$31\frac{3}{16}$	$12\frac{1}{4}$	Parabolic Mirror
36	110	37	$14\frac{3}{4}$	Parabolic Mirror
60	200	....	....	Parabolic Mirror

Range. — The dimensions of the object, the color, form, and nature of its surface, the degree of contrast with surroundings, the influence of telescope, glasses, or spectacles, and the physiological peculiarities of the observer's eye all have a bearing upon the range at which a beam is effective. These factors have been analyzed, and it has been found that the range increases even less rapidly than the fourth root of the intensity. To increase the range five-fold, under atmospheric conditions giving 70 per cent transmission per kilometer, it is estimated that the intensity would have to be increased 42,000-fold for typical military work.

Color. — The impression prevails that blue light is particularly desirable in the rays of a searchlighting beam, since the surfaces observed are often bluish-gray and because of the Purkinje effect. Whenever a preponderance of blue rays is reflected an advantage probably exists; but in the usual case it would seem to be detrimental since the eye will not focus for the blue rays when the longer wave-lengths predominate, and vision is, therefore, impaired.

Arc Electrodes. — Prior to the late war, the positive electrodes for the carbon arcs used with 60-inch mirrors were about 2 inches in diameter. This resulted in a beam spread of about 2.5 degrees. The intensity of the beam from these searchlights was of the order of 30 to 40 million candlepower. Through developments in the manufacture of the electrodes and in increase of current density through reduction in the diameter of both positive and negative electrodes, the beam intensity was very greatly increased. High current density and small crater size result in high intrinsic brilliancy and beam intensity. The efficiency is increased as the diameter of the negative electrode is decreased and the arc lengthened, with the accompanying reduction in the angle

of shadow. The small negative is also advantageous in steadying the arc. The high current density required in a small negative is accomplished without spindling by providing this electrode with a copper coating. The diameter of the positive electrode was brought down to $1\frac{1}{8}$ inches for an arc of 200 amperes. The result of these developments was an increase in the candlepower of this lamp in a 60-inch searchlight to about 125 million; at the same time equilibrium conditions were obtained more rapidly after starting, the arc made more steady, and the spread of the beam kept down to 1.5 degrees, thus greatly aiding vision.

Flame Arcs. — Shortly before the war, the high-current flame arc lamp for searchlight use was developed. This lamp is used with automatic feed for naval and coast defense applications; but for open-field, war conditions, the more simple and more rugged hand-operated lamp is utilized. With a 60-inch mirror the lamp gives a narrow beam with a candlepower of the order of 400 million. It is this lamp that is utilized in connection with the light, 60-inch, portable equipment previously referred to, as well as in a 36-inch naval unit and a 30-inch open-type projector mounted on a tripod with a total weight of but 250 pounds.

Mirrors. — A feature of the modern portable type of searchlight is the metal mirror. This type has the advantages of lighter weight, far less expense, freedom from cracking with heat, or shattering when struck by a bullet. A spun or pressed metal reflector could not be made with the necessary accuracy, but a simple means of turning out exceedingly accurate mirrors in any quantity desired was developed during the war, through the deposition of silver on the convex side of a glass form for a glass mirror, the silver being built up electrolytically and then plated with copper to a considerable thickness, after which adhesive is applied to the copper and backed with a plastic coating with suitable reinforcement. The mirror is then removed from the glass form and is found to have an unexcelled degree of polish. Coating the surface with lacquer makes it possible to store the mirror as long as desired. When the mirror is put into use, however, the heat from the lamp soon evaporates this lacquer and the surface of the mirror gradually tarnishes, giving the mirror but a short service life. One of the chief advantages of the metal mirrors is the fact that production of glass mirrors is very much limited because of the nature of the glass polishing and other processes involved, whereas any desired production of the metal mirrors can be built up very rapidly.

Since the thickness of the glass mirror results in some refraction of the beam, it has been found necessary to modify the contour of the convex surface slightly from that of a paraboloid to compensate for this

refraction and keep the beam as narrow as possible. The accuracy of contour is tested by projecting a small beam of light parallel to the axis of the mirror and passing it across the mirror to ascertain whether the reflected beam from all positions passes through the same point or focus. A further test to determine whether the mirror is uniform and free from irregularities is to photograph the reflection in the mirror of a screen ruled with lines at right angles.

Incandescent Lamps. — The filaments of incandescent lamps do not have a sufficiently high brightness to make their use feasible in searchlights for military purposes. For commercial and navigation purposes, however, they have a considerable field in conjunction with 18-inch, 24-inch, and 30-inch parabolic mirrors. The candlepower values in the beam are not so high as can be obtained with carbon arcs in mirrors of these sizes. However, the units have the advantage of steadiness of beam and simplicity in operation, which in many situations are of greater importance. The light source is more concentrated in lamps of high current and low voltage, and, because of the greater brightness and small dimensions of the source, higher beam candlepower and narrower divergence result. For some commercial purposes the greater spread obtained with lamps of higher voltages is, however, of advantage. Results obtained with incandescent searchlights are indicated in Table LIX.

TABLE LIX

DATA ON INCANDESCENT SEARCHLIGHTS

Nominal Mirror Diameter	Lamp	Beam Spread	Candlepower Center of Beam
18″	1000-w., 115-v.	$4\frac{1}{2}°$	1,650,000
18″	900-w., 32-v.	$3\frac{1}{2}°$	4,000,000
18″	1200-w., 12-v.	$3\frac{1}{2}°$	5,000,000
30″	1200-w., 12-v.	$2\frac{1}{2}°$	15,000,000

LIGHTHOUSES

Lighthouses exist for the purpose of orientation. Reliability, simplicity, and low cost of operation, rather than extremely high intensities, are the primary requisites in the majority of cases.

Systems. — Lights are usually classified, according to their characteristic appearance, as fixed lights, the rays of which are concentrated into a belt of light distributed evenly around the horizon; flashing lights, the rays of which are concentrated into a pencil or cone with a small angle, directed toward the horizon, and revolved about the light source

as a center; and sector or range lights, in which the light is concentrated into a cone of light with a small angle, that is, maintained in some definite direction. It is of advantage to give each light a characteristic appearance, in order that it may be easily recognized by mariners and not confused with other lights or shore stations. Fixed lights, therefore, have been largely converted into occulting lights, which appear and disappear at characteristic intervals; one means of producing this effect is by a cylindrical screen, fitted over the light source and rapidly raised or lowered.

Lenses. — Lens systems form the standard equipment, and their application in this field is notable for the large effective angles and hence

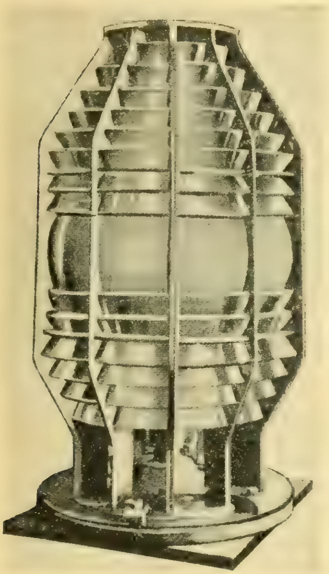


FIG. 143. Fourth-order Six-panel Fixed Lens.

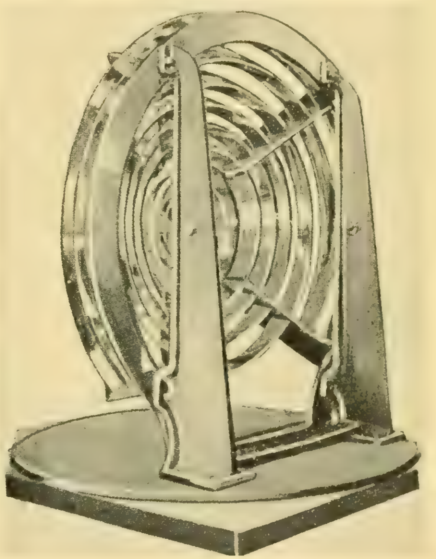


FIG. 144. Fourth-order Range Lens.

the high efficiencies obtained. The careful correction of these lenses has led to a degree of control which is surprising in view of the extended sources of relatively low intrinsic brilliancy employed. The lens systems are divided into " orders " according to their focal length, ranging from 150 mm. (5.9 inches) for the sixth order to 920 mm. (36.22 inches) for the first and 1330 mm. (52.36 inches) for the hyper-radial.

For fixed or occulting beams giving a band of light continuous in a horizontal plane, the lenses are cylindrical in form about a vertical axis (Fig. 143). The light issues as a belt of narrow vertical divergence;

this angle and the intensity of the beam vary directly with the focal length for a given light source. The central part of a typical lens covers an angle at the source of nearly 60 degrees and contributes about 60 per cent of the light. This portion of the lens is dioptric, redirecting the light by refraction only. The upper and lower parts of the lens system are catadioptric, acting by both refraction and total reflection. The lower prisms cover about 20 degrees and furnish 10 per cent of the beam; the upper nearly 50 degrees and 30 per cent of the light. Frequently a dioptric belt of about 80 degrees effective angle is employed alone.

FIG. 145. First-order Double Flashing Apparatus.

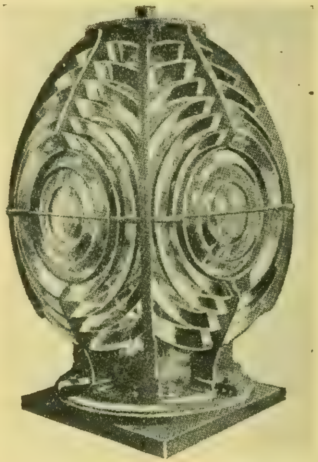


FIG. 146. Fourth-order Four-panel Lens.

If lenses developed about a horizontal axis are used, both vertical and horizontal concentration are secured and a very intense narrow cone of light results, varying for a given source roughly as the square of the focal length of the lens. Such a hemispherical lens, Fig. 144, with a spherical mirror on the opposite side of the source, gives a powerful beam in one fixed direction, as for range lighting. If rotated about the light source, it produces a flashing light. A great advantage of this flashing lens is the enormous increase in beam intensity realized. Two such lenses, Fig. 145, give high-intensity beams at a 90-degree angle and are rotated about the source to produce high-powered flashing effects. Sometimes four-sided lens systems are used (Fig. 146). It is interest-

ing to note that the larger lens systems are often floated in mercury to facilitate turning. An example of this practice is in the light at Cape Race, Newfoundland, where a lens system weighing 7 tons is floated on some 950 pounds of mercury. A clockwork mechanism drives it at a definite speed of rotation.

Recent tests by the French Lighthouse Service indicate that metal mirrors of modern design give results superior to those obtained with lens systems.

Light Sources. — A fire of coal or wood, set in a brazier or grate, was the earliest form of illuminant used in lighthouses. Tallow candles were then used, followed by oil lamps with flat and cylindrical wicks. Lamps were developed with three or four concentric cylindrical wicks. Sperm oil, olive oil, lard oil, colza oil and cocoanut oil have been variously employed as fuels in various parts of the world. Incandescent mantles, burning vaporized kerosene, are used in the majority of lighthouses today. These provide a relatively high brilliancy and small source, and operate at the lowest cost of any lamp used for this service. Gas, usually with the incandescent mantle, has been used to some extent. Pintsch gas and acetylene are used in some instances, particularly on rough service, as on light buoys.

From an optical standpoint, the electric arc and concentrated filament incandescent lamps are most nearly ideal. The first electric installation made use of the electric arc, and a number are still used on important lights where high intensity is a requisite. Owing to the fact that the light is generally located in a position remote from central station service, it is often necessary to provide a generating plant at the light.

The incandescent lamp has been installed comparatively recently in a number of lighthouses. The 1000-watt, 115-volt gas-filled tungsten lamp of standard filament construction has given excellent results in several of the more important lights. The advantages of this source are its more desirable color and great beam candlepower, together with its ease of control and supervision. It is a simple matter to control the lamp current by an ordinary sign flasher and to produce flashes at any desired interval and frequency. Where the incandescent lamp has been installed with existing lenses, particularly of the longer focal distances, designed for use with kerosene flame burners of large areas, better results have been obtained by using a spherical mirror beneath the lamp to reflect the light properly to the upper catadioptric rings of the lenses. Incandescent lamp equipments of various sizes are used on the larger light vessels.

Range. — The distance at which a light is visible at sea is limited by the eclipsing of the light by the curvature of the earth; the intensity

and color of the source are also factors. As the density of air varies with elevation, the rays of light suffer successive refraction and consequently travel curved paths, concave downward. This has the effect of making the light visible for a greater distance than a tangent drawn to the earth's surface would indicate. If the eye of the observer is at

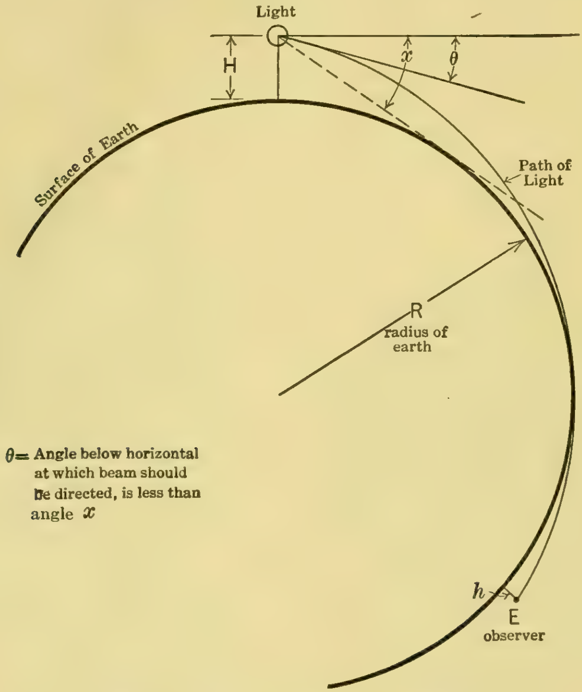


FIG. 147. The Geographical Range.

E, Fig. 147, a distance of h from the earth, the maximum distance at which he can see the light may be obtained from the formula,

$$\text{Distance} = \sqrt{\frac{RH}{0.42}} + \sqrt{\frac{Rh}{0.42}}.$$

In setting up a light to be used for landfall purposes (where the mariner uses it to estimate his distance offshore at the time that it is first sighted) it is, of course, necessary to use a light of sufficient candlepower to be visible at least the distance of the geographical range.

Because of the great distance of an observer from the light, questions of visibility here pertain to a point source, that is, one subtending an angle less than the limit for the resolving power of the eye. It has been found that the visibility of a point source is proportional to the candlepower

and inversely proportional to the square of the distance, and that visibility is independent of brightness for sources subtending an arc of less than 2 minutes. A recent investigation has shown values for the range of lights of different colors only slightly less than the following, reported by the German Lighthouse Board of Hamburg as a result of their tests in 1894:

$R = 1.53\sqrt{I}$ for white light in clear weather, where R represents the range in miles and I the candlepower.

$R = 1.09\sqrt{I}$ for white light in rainy weather.

$R = 1.63\sqrt[3]{I}$ for green light in clear weather.

Color. — Greens and blues are, in general, considered as unsuited for lighthouse service, because of the absorption by the color screens and the relatively poor transmission of these colors through foggy atmospheres. The absorption of the red screens commonly used in lighthouse service is in the neighborhood of 60 per cent; green screens absorb some 75 per cent. The use of color, therefore, reduces the candlepower tremendously. Water vapor (fog) scatters the shorter wave-lengths of light and tends to transmit only the reddish rays from the original light source. Therefore, a white light should be of as white or bluish-white quality as possible, in order that on foggy nights it may not be reddened enough to be confused with red beacons.

Candlepower. — Under ordinary atmospheric conditions, relatively low intensities suffice for visibility at the geographical limit. In stormy and foggy weather, however, when a light is most needed, considerably higher intensities are required for the light to be effective. Furthermore, the increase of visible range through heavy fog becomes very gradual as the candlepower is increased. Hence, extremely high intensities are often found at important lights. Many of the larger incandescent-mantle oil lanterns give beam intensities of the order of several hundred thousand candlepower. Electric units give beams that are measured in millions. In many installations the duration of the flash is 0.1 second or even less. This is probably shorter than the time required at low illuminations to produce the same sensation as a steady beam of the same intensity. The results produced by different durations of flash and intervening periods are only partially known; nevertheless, for maximum utilization of a source at range limits, short flashes are required.

There is a marked tendency toward using numbers of light buoys instead of erecting a few lighthouses of high intensity. With Pintsch gas or acetylene, these buoys frequently operate without attention for periods as long as nine months or a year. They can be made to flash

by means of a mechanism, actuated by the gas pressure, which turns the main burner off and on. With the large buoys it is also found economical to use "sun valves," which turn off the main burner during the period of daylight radiation.

Beacon lights are now being used extensively to guide aëroplanes in night flying. In this case the beacon itself needs comparatively little altitude, since the observer is flying at a height which gives him a very large geographical range. For example, to an observer flying at 4000 to 5000 feet, very customary levels, the geographical range of a light at the earth's surface is some 85 miles. Placing the light on an eminence, of course, further increases the visible range. With such a long range it is desirable to have a light of high intensity.

MOTION PICTURE AND SLIDE PROJECTION

The application of light for the projection of transparencies, either lantern slides or motion picture film, is a subject of immediate interest to practically everyone. In recent years, the latter has become the more general application.

Principles of Projection. — Optically, apparatus for motion picture projection comprises essentially a light source and condensing lens, a photographic print on a transparent film, a projection objective lens,

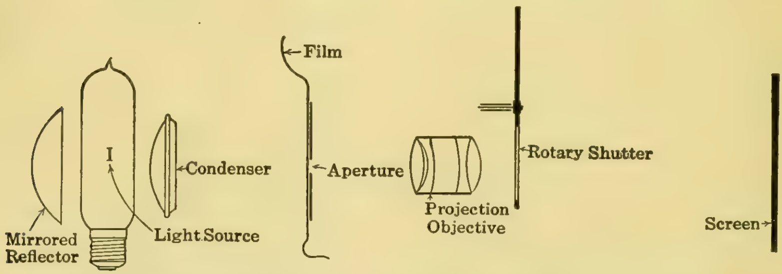


FIG. 148. Essential Optical Elements for Motion Picture Projection with Incandescent Lamps.

and a screen, supplemented by a rotary shutter, an aperture plate, and in certain cases a mirrored reflector. These optical elements are shown in their respective positions in Fig. 148. A motion picture projector has, in addition, the mechanism for rapidly bringing successive pictures into position at the aperture and stopping them for a fraction of a second while they are projected as enlargements on the screen. These follow each other so rapidly (usually at the rate of about sixteen per second) that the eye does not distinguish individual pictures, but apparently beholds the motion in the scene photographed.

Projection Lens. — In projection, the operation resulting in a defined image is known as focusing. The combination of glass elements used to accomplish focusing is known as a projection objective lens. Such a lens produces an image only in one plane, and its distance from the lens depends upon the contour of the glass surfaces as well as upon the distance between the object and the lens. (See Fig. 149.)

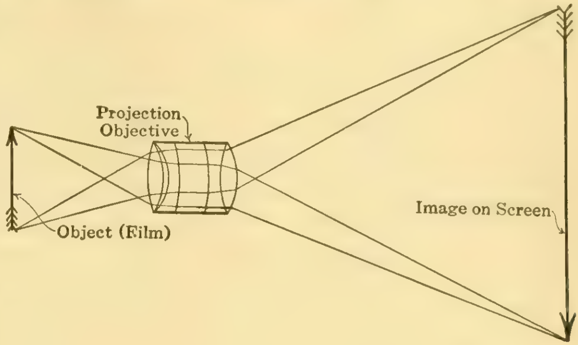


FIG. 149. The Projection Lens — Light Reaching Any Part of the Lens from a Single Point on the Arrow is Focused at Only One Point on the Screen.

If an image is to appear as bright as possible, the screen on which it is shown must have a surface which reflects a maximum amount of the incident light in the direction of the observers.

The area of the image on the screen in motion picture theatres is usually from 25,000 to 60,000 times that of the print on the film. Moreover, the projection lens absorbs some of the light and nearly one-half of the remainder is absorbed by the rotating shutter, with the result that the quantity of light passing through a unit area of the film, even when all of it is directed to the objective, must be from 70,000 to 170,000 times that received by each unit area of screen.

Condensing Lens. — It happens that there are no sources which of themselves direct more than a small percentage of their light into the

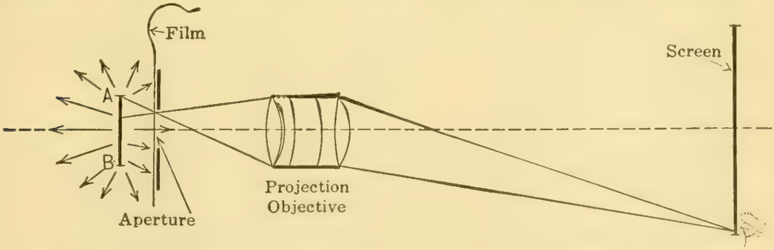


FIG. 150. Source Size Requirements — Source AB must be larger than the aperture to send light through a point at the edge of the aperture and through the full opening of the objective lens.

small angle included by the projection lens. Moreover, the heat radiated and conducted from the source (Fig. 150) would unduly raise the

temperature of the film and its guides. Here the refractive properties of glass in a lens called the condensing lens may be employed to intercept the light emitted through a wider angle from a small source placed back from the aperture and to direct it through the film to the projection lens. By the proper design of the curvature of the faces of such a condensing lens, it can be made of relatively large diameter with respect to the source dimensions and thus become both a large apparent source and a means of utilizing a large amount of the total light flux. The diameter of the condensing lens for various distances from the film is determined by the requirement that, for uniform screen illumination, equal areas of the lens must be visible through the optical system from all points of the screen (Fig. 151).

The converging beam from the condenser forms an image of the source at the point where the rays cross; as this is also at or near the narrowest part of the beam, the aperture should be placed at this point in order that the greatest amount of light may pass through it, for

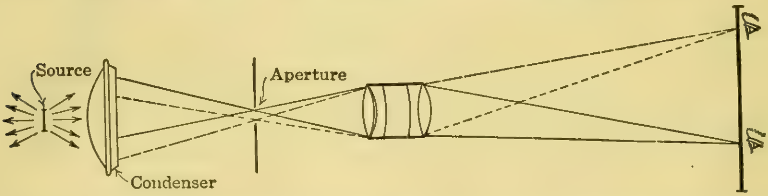


FIG. 151. Condenser Size Requirements — For uniform screen illumination the size of the condensing lens must be such that equal areas of uniformly bright light source are seen on looking back from each point on the screen.

with sources employed in practice the cross-section of the converging beam from the condenser is, even at its narrowest part, usually equal to or greater than the area of the film. If the source is not of uniform brightness, the film placed at this position will not be evenly illuminated.

The aperture plate is a metal plate with an opening slightly smaller than a single picture of the film; it serves to limit the light beam to the single picture being projected.

Film Movement. — With the intermittent mechanism commonly employed for moving the film, the picture is in movement from one-fourth to one-fifth of the time. When sixteen pictures are projected per second, this means that approximately one-hundredth of a second of movement is followed by five-hundredths of a second with the picture in place. If the light were allowed to reach the screen during the period of movement, flicker and blurring of the picture would result. Provision is, therefore, made for cutting off this light by means of a rotary shutter.

Properties of the Component Elements

Light Source. — Since the film aperture and projection lens present openings of considerable area, there is no necessity for keeping the light source unduly small. The maximum size of source which can be employed effectively with a given optical system is dependent on the refracting powers of the condensing lens, the size of the aperture opening, the size of the projection lens, and the distance of the aperture from the condensing and projection lenses. A source of size AB, Fig. 152, projects a beam $A'B'$ at the aperture, all of which passes through; the larger source CD will send a greater amount of light through the opening, but the source EF produces a beam $E'F'$ at the aperture so large that but a small part passes through and the remainder of the light is

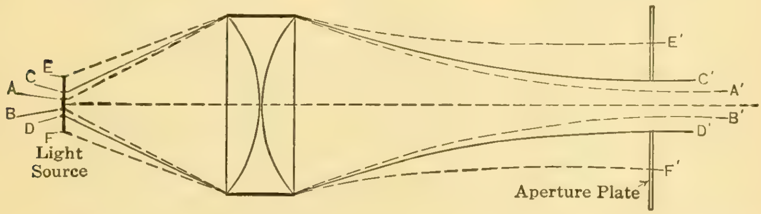


FIG. 152. For a given condensing lens, the size of the beam at the aperture plate is proportional to the size of the light source.

wasted. Circular or rectangular sources, having maximum dimensions as large as $\frac{3}{4}$ inch, are commonly employed.

Four light sources are used in motion picture projection in theaters and large auditoriums: the alternating-current carbon arc, the direct-current carbon arc, the high-intensity flame arc, and the incandescent lamp.

Arc. — Of the arcs, the alternating-current lamp is the least efficient for projection work, since the light emitted is divided equally between two carbon craters as sources and only one crater can be placed in the optical system where its light is directed effectively in useful angles, and the major part of the light from the other is lost. With the direct-current carbon arc, most of the light is emitted by the positive electrode crater; the carbon ar usually tilted at an angle of about 25 degrees with the vertical (Fig. 153) to direct a maximum amount of light from the positive toward the condensing lens. The carbons must be frequently moved toward each other as they are slowly burned away; a mechanism for accomplishing this feeding by hand is usually employed, although a separate mechanical control is sometimes used. A typical direct-current lamp is shown in Fig. 153. In the high-intensity (direct-

current) flame arc, the positive electrode is mounted horizontally and is slowly rotated by a small motor connected across the arc to maintain uniform burning of the special cored electrode; automatic feeding is maintained by mechanical energy from the same source.

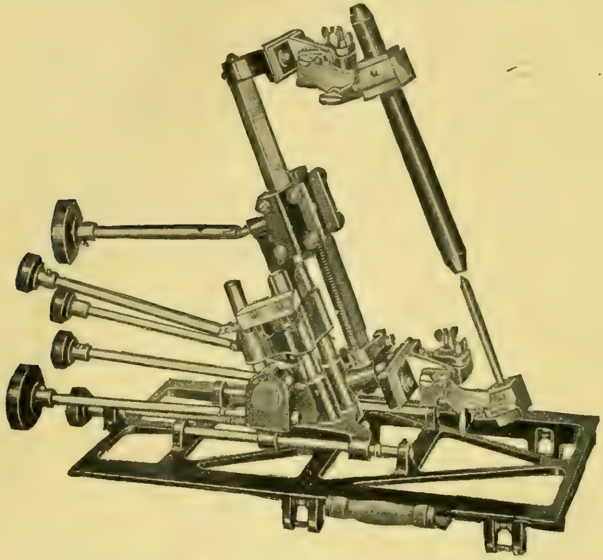


Fig. 153. Direct-current Arc Lamp with Mechanical Controls, for Motion Picture Projection.

The carbon diameters commonly employed for various arc lamp operating currents are shown in Table LX.

TABLE LX

Carbon Diameters for Motion Picture Arc Lamps

Current Amperes	Positive Diameter	Negative Diameter
40–60 a.c.	$\frac{5}{8}$ in. (both carbons)	
60–75 a.c.	$\frac{3}{4}$ in. (both carbons)	
75–100 a.c.	$\frac{7}{8}$ in. (both carbons)	
25–50 d.c.	$\frac{5}{8}$ in. cored	$\frac{5}{16}$ in.
50–65 d.c.	$\frac{3}{4}$ in. cored	$\frac{11}{32}$ in.
65–70 d.c.	$\frac{7}{8}$ in. cored	$\frac{11}{32}$ in.
70–85 d.c.	$\frac{7}{8}$ in. cored	$\frac{3}{8}$ in.
85–100 d.c.	1 in. cored	$\frac{7}{16}$ in.
50 flame	9 mm. cored	$\frac{5}{16}$–$\frac{11}{32}$ in. Metal Coated cored
75 flame	11 mm. cored	$\frac{11}{32}$–$\frac{3}{8}$ in. Metal Coated cored
100–120 flame	13.6 mm. cored	$\frac{3}{8}$–$\frac{7}{16}$ in. Metal Coated cored

Incandescent Lamp. — The incandescent lamp source consists of four parallel segments of coiled tungsten wire, as shown in Fig. 154. With the plane of the filament placed parallel to the condensing lens, equal amounts of light are directed toward and away from it. The coil segments are separated in order to prevent short-circuiting, which breaks up the uniformity of the light source. A spherical mirrored glass reflector is placed behind the lamp so that the filament is at the center of curvature; it turns back about 80 to 85 per cent of the light striking it. This light is brought to a focus in the plane of the filament as an inverted and reversed image of it (Fig. 155), producing in effect a solid, luminous rectangle; evenness of screen illumination is thereby obtained, with the added advantage that the screen illumination is increased from 65 to 75 per cent.

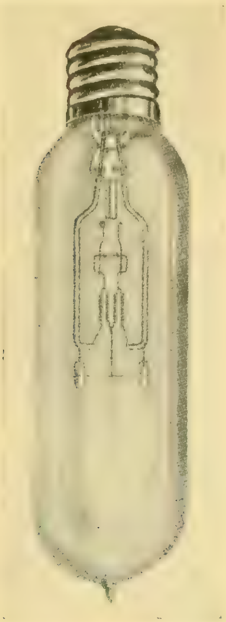


Fig. 154. 900-Watt, 30-Ampere Motion Picture Tungsten Incandescent Lamp. The 600-watt, 20-ampere lamp is similar in appearance.

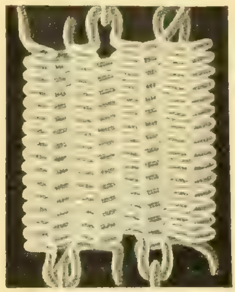


Fig. 155. The Reflected Image of Filament Segments Intermeshed with the Coils.

Incandescent lamp data are given in Table LXI.

TABLE LXI

Motion Picture Incandescent Lamp Data

Watts	Amperes	Volts	Bulb Diameter*	Overall Length	Base
600	20	28–32	$2\frac{1}{2}$ in.	$9\frac{1}{2}$ in.	Mogul
900	30	28–32	$2\frac{1}{2}$ in.	$9\frac{1}{2}$ in.	Screw

* Tubular bulb

Table LXII gives screen illumination data for various arcs and the incandescent lamp. The data are typical for average operating conditions; under other conditions, higher or lower values will apply, since the actual results obtained in service will vary with the size of the picture, the distance it is projected, and the skill of the operator.

TABLE LXII

Screen Illumination Data for Motion Picture Illuminants

Light Source	Light Flux Projected to Screen — Lumens*
35-ampere D.C. Arc	850
50-ampere D.C. Arc	1050
75-ampere D.C. Arc	1250
100-ampere D.C. Arc	1450
900-watt, 30-ampere Incandescent Lamp	1150
50-ampere Flame Arc	1400
75-ampere Flame Arc	2700

* Beam unobstructed by rotary shutter or film.

Condensing Lens. — The larger the diameter of a condensing lens of a given refracting power, the more light it will pick up. But with increased diameter, the thickness also becomes greater, and very thick lenses have excessive spherical aberration. A moderate amount of spherical aberration is an advantage in that it produces a smaller beam at the aperture position, but if it is so marked that a considerable part of the light is directed outside the projection lens, the gain in light intercepted by the greater diameter is soon lost.

Fig. 156. Plano-convex Condensing Lens Combination.

With the arc lamps the $4\frac{1}{2}$-inch diameter plano-convex combination shown in Fig. 156 is employed. The arc is placed about $3\frac{1}{2}$ inches or farther away from the nearest condenser to prevent excessive breakage and to reduce the deposit of slag on its surface. With the incandescent lamp the modified Fresnel or prismatic condenser shown in Fig. 157 can be used with two marked advantages over spherical combinations of similar refracting power: it can be made to intercept a larger amount of light flux; and the light from each ring can be focused at a different

distance from the condenser so that no well-defined image of the source appears and uniform illumination of the film is obtained.

A development which combines high refractive power with reduction in aberration and makes possible a system intercepting a larger angle of light employs other than spherical surfaces for the lenses. The aspheric condenser shown in Fig. 158, designed for use with incandescent lamps, directs about 50 per cent more light through the optical system than does the prismatic; in addition to the advantages resulting from the

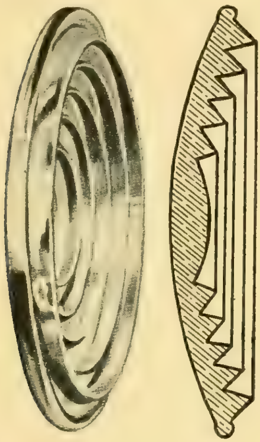


Fig. 157. Prismatic Condensing Lens for Motion Picture Projection with Incandescent Lamps.

Fig. 158. Aspheric Condensing Lens Combination.

aspheric surfaces, the larger-diameter second element receives essentially all of the light passed by the first unit.

A projection lens must be essentially free from chromatic aberration; but in the case of condensing lenses the projection of aberration colors to the screen can be avoided by intercepting the edge of the beam and using a lens of such design that the source is not focused as an image at the aperture if it is of non-uniform brilliancy.

Aperture. — The standard aperture is a rectangular opening 0.6795 inch high and 0.906 inch wide. The aperture plate, across which the film moves, must for best efficiency be located where as much as possible of the converging beam from the condensing lens will pass through the opening and at the same time be uniformly distributed over this area. In practice a light beam larger in diameter than the diagonal of the aperture opening must, therefore, be used, since the light near the edge of the beam is of somewhat lower intensity and shows color due to

chromatic aberration from the condensing lens; this part must, therefore, be intercepted.

Projection Objective Lens. — The desired size of the objective lens depends on the size of the light source and the convergence of the beam from the condenser, which determines the spread of the rays passing through the aperture. This convergence is less with the plano-convex condensers used with arc lamps than for the incandescent-lamp condenser systems. For the latter, when the longer focal length objective lenses are employed with the longer projection distances, about twice as much light will be projected by using the large diameter objectives known as the No. 2 size.

By combining suitable optical glasses in elements of proper thickness, surface curvature, and spacing, the units can be given the following characteristics: freedom from spherical aberration, providing good definition; flatness of field, producing equally sharp images over the entire screen picture; and freedom from chromatic aberration, eliminating colored fringes on the screen image.

The focal length of the objective lens determines the picture size for a given throw. With the width of the picture selected, the focal length of the required objective lens is given with sufficient accuracy for practically all purposes by the approximate formula[1]

$$\text{Equivalent focus (inches)} = \frac{\text{Throw (ft.)} \times 0.906}{\text{Picture width (ft.)}}.$$

The throw is measured from the center of the objective to the screen; the formula applies for an aperture of standard size.

Screen. — For the projection of a satisfactory picture it is necessary to provide a screen which will effectively direct the light to the audience so that the images there formed may be seen without effort from every seat. It is desirable that the screen surface have a high reflection-factor, but it is even more important that it direct a maximum part of the light back within the solid angle in which all of the seats are included, and that the light be so distributed within this angle that the screen will appear as nearly as possible equally illuminated from all of the seats. In the wide theaters the outer seats in front often make an angle of 60 degrees with a normal to the screen; in the narrower houses the angle is sometimes as low as 30 degrees, as shown in Fig. 159; in the vertical plane the lowest front seats are occasionally as much as

[1] The exact formulæ are:

$$EF = \frac{12\,T}{1 + 13.25\,W} \qquad T = \frac{EF}{12}(1 + 13.25\,W) \qquad W = \frac{0.906\,T}{EF} - 0.0755$$

where EF = Equivalent focus (in.) T = Throw (ft.) W = Width of picture (ft.)

35 degrees below a normal to the screen and the highest seats 30 degrees above it.

The distribution of light from a screen surface can be controlled by choice of material, its finish, texture and configuration. The screens so far available meet the requirements fairly well in many theaters but

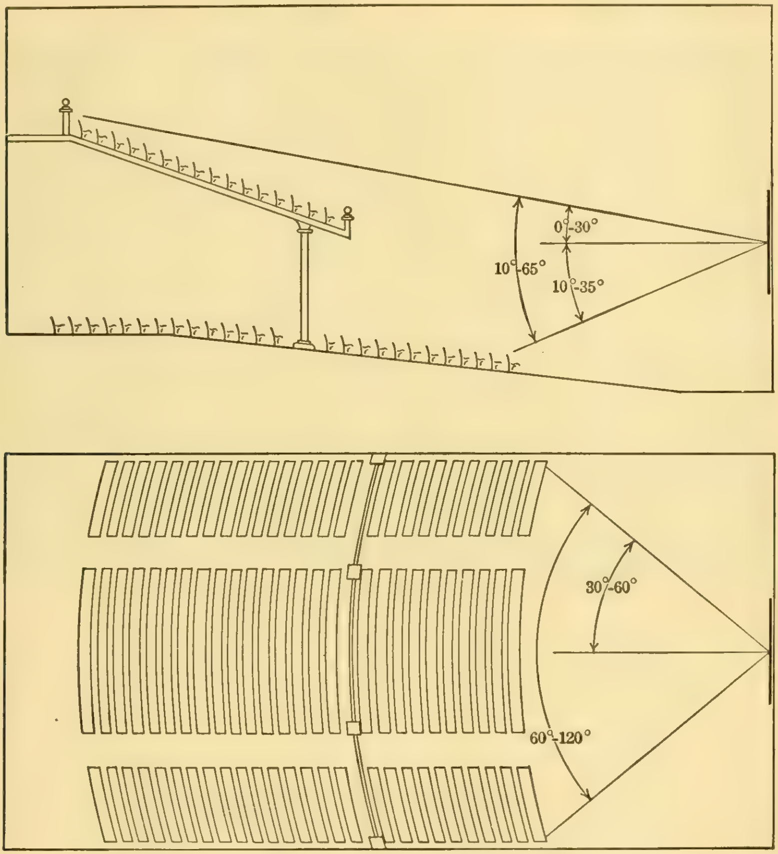


Fig. 159. Representative Angles Within which the Screen Must Direct Light to the Observers.

somewhat imperfectly in others; that is, there is not so great a diversity of light-reflecting characteristics as would be desirable for greatest efficiency in each case. The three principal types in use are shown in Fig. 160 together with curves indicating the relative brightness as viewed from the different angles when a unit quantity of light is directed in a beam normal to the screen. Thus, at right angles to the surface, the matte diffusing screen has a brightness of 1.0 unit and this is main-

tained at 0.94 unit at 30 degrees from the normal, and falls only to 0.9 at 60 degrees; the semi-matte metallic surface, on the other hand, has a brightness of 3.5 units at right angles to the screen, but at 30 degrees it is reduced to 0.8 unit, and at 60 degrees it is only 0.25 unit. It should be noted that the areas included within the several curves are not at all proportional to the amount of light reflected from each screen.

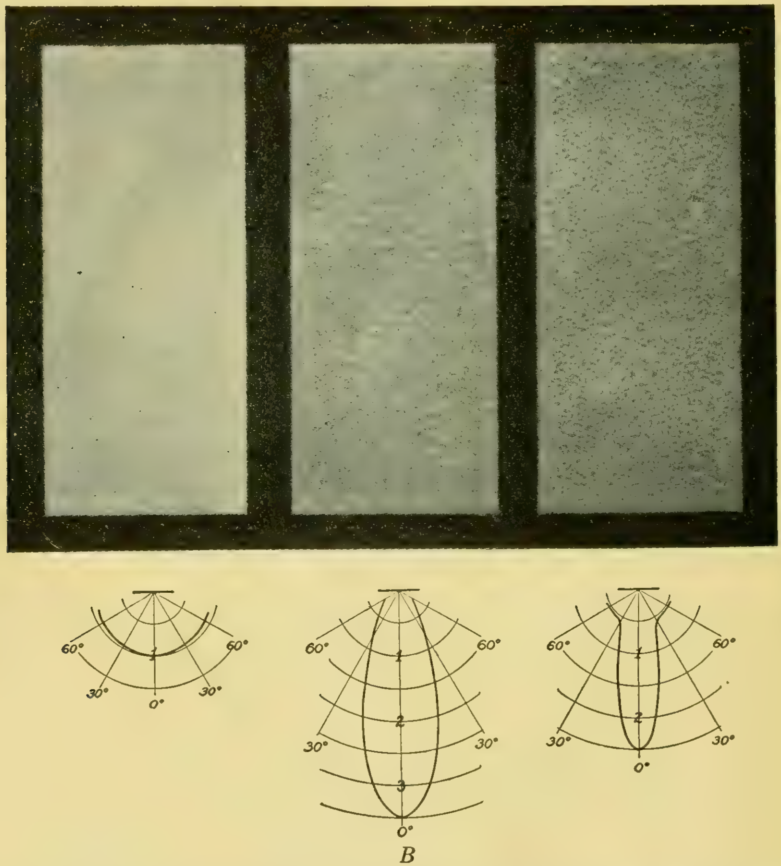


Fig. 160. Three Representative Screen Surfaces and Brightness Distributions when Equal Quantities of Light are Directed in Beams Normal to the Surface.
A — White Diffusing Surface. *B* — Semi-Matte Metallized Surface. *C* — Beaded Surface.

Since, with the matte diffusing surface shown in Fig. 160, the maximum brightness is well maintained at all angles, a screen of this characteristic is especially adapted to very wide theaters. Although the outside front seats may lie 65 degrees from the normal, the brightness

in their direction is about 90 per cent, and the average brightness for all of the seats is 96 per cent of the maximum. In general, the diffusing surfaces should be used where a considerable portion of the seats lie more than 40 degrees from the normal to the screen.

The smooth metallized surface, Fig. 160 and Fig. 161, *B*, is especially applicable for the narrower houses. For a typical theater of this type with the front end seats about 40 degrees from the normal, 97 per cent are within 30 degrees, at which angle the brightness is still 0.8 unit, and 87 per cent are within 20 degrees, where the value is 1.6 units. The average screen brightness as viewed from the seats of this theater will, therefore, with this type of screen, be $2\frac{3}{4}$ times what it would be with the diffusing types. The more usual case is that of the theater of medium width where the end front seats make an angle of about 50 degrees with the normal. But even here 88 per cent of the seats fall within 30 degrees of the normal and all of these seats receive more light from screen *B* than from screen *A* (Fig. 161), in fact about $2\frac{1}{2}$ times as much for the average. For the remaining 12 per cent, the screen appears only about one-half as bright as would one of the diffusing type.

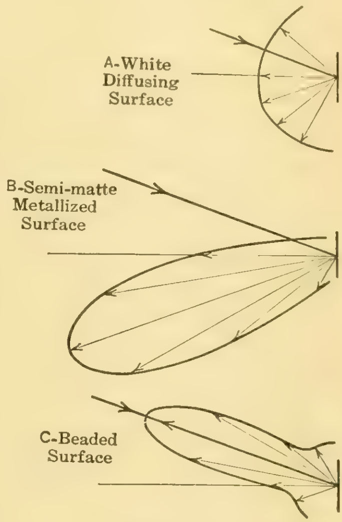


FIG. 161. Reflection Characteristics of the Three Types of Screen Surfaces when the Beam from the Projector is Directed to Them at an Angle.

The beaded surface, Fig. 160, *C*, and Fig. 161, *C*, has a somewhat lower maximum brightness than the semi-matte metallic surface, but higher values at angles of about 35 degrees and beyond. The beaded surface finds its best application in theaters of medium width.

In the foregoing, reference has been made only to the light distribution in the horizontal plane, but since the seats are at various elevations, the brightness distribution in the vertical plane must also be considered. This is especially important in view of the fact that the three types of screen surfaces act differently in reflecting the light received at an angle with a normal to the surface. From the metallic-surface screens, for example, the reflection is to a considerable extent specular, as from a mirror; that is, the general direction of the reflected beam makes an angle with the normal equal to the angle of

incidence, as in Fig. 161, *B*. The bead screen reflects a maximum brightness in the direction of the projector, as shown in Fig. 161, *C*, because the specular part of the reflection is largely from that part of the glass bead surfaces normal to the beam. Obviously this screen finds its best application in theaters where the seats are not far below the projected beam. The direction from which the incident light is received has little effect on the distribution from the diffusing screen, as shown by Fig. 161, *A*. It is evident that the proportions of the theater, the range of seat elevations, and the position of the projection room with reference to the stage must, therefore, all receive careful consideration in the selection and mounting of the screen.

The screen brightness necessary to produce the best pictures varies with the reflecting characteristics and texture of the screen surface employed and is limited on the one hand by the amount of light required for satisfactory observation of dense film and on the other hand by the amount of reflected light which will produce glare. What values are best depends on the included angle the screen makes with the eye and on the position in the house in which the observer is sitting. In general, that value is satisfactory which is above the minimum required for the rear seats and below that which produces glare from the front seats. The most satisfactory brightness appears to be materially lower with a diffusing type of screen than with those giving a pronounced directional distribution. This tends to make the results with the diffusing screen relatively better than would be indicated from the respective brightness values given in the above discussion. Although for a given light source the screen brightness decreases somewhat with the larger pictures, there is a compen ating factor in that the brightness required for a good picture decreases as the size is increased.

Illumination of the Theatre Auditorium. — The illumination of the auditorium during the projection of the picture vitally affects the required screen brightness, and the selection and placing of the lighting equipment must, therefore, be treated as a phase of the projection problem. There must be sufficient light to create an agreeable atmosphere and to permit the theatre patrons to find or leave their seats safely during the projection of pictures; yet the eye should encounter no very bright areas, and the light directed to the screen from fixtures or vertical surfaces facing the stage should be kept at a minimum in order that contrasts in the screen picture may not be materially affected.

A moderate intensity of general illumination near the front of the theater, of the order of one-tenth of a foot-candle, does not materially affect the picture if this intensity is not allowed to reach the screen.

Auxiliary Projector Lamp Equipment. — Alternating-current arc lamps are usually operated from a hand-controlled regulating transformer and other control apparatus is not required. On alternating-current circuits, the direct-current carbon and flame arcs are operated from a motor-generator set. On direct current, only a series resistance is ordinarily employed. Incandescent lamps are most economically operated on alternating-current commercial lighting-and-power cir-

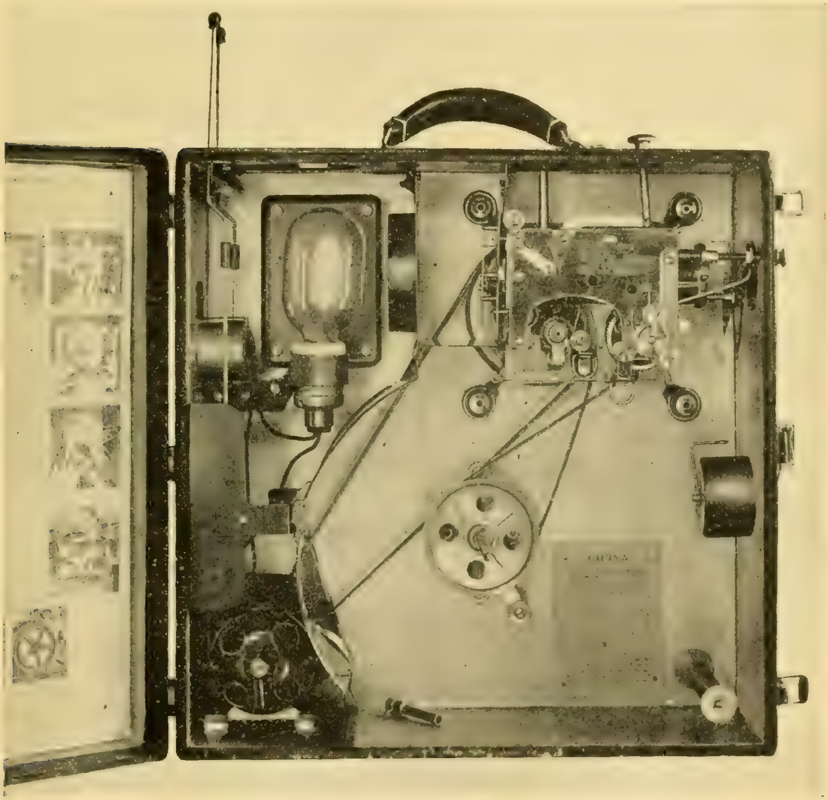


FIG. 162. Portable Motion Picture Projector.

cuits from a hand-controlled transformer regulator; an ammeter is required to maintain the lamp current at its rated value. On direct current a rotary converter for changing the direct to alternating current for the transformer regulator provides the most economical method of operation.

Portable Motion Picture Projectors. — Portable motion picture projectors are adapted especially for use in the school classroom and

laboratory, for homes, and for the traveling lecturer and salesman. Optically they are not essentially different in principle from the theater sizes; they differ mainly in the reduced size and proportions of the various elements, and in the relatively smaller diameter and distance of the condensing lens from the aperture. A smaller aperture and film is employed with slow-burning film on some equipments.

Incandescent lamps are used exclusively. For the services where these projectors are employed, the use of auxiliary equipment must be kept to a minimum and 110–120-volt lamps are employed wherever possible. With some equipments of the most compact type, the more concentrated-filament, low-voltage lamps are used in conjunction with a small rheostat in order that maximum screen illumination may be obtained from a small lamp. A typical portable projector is shown in Fig. 162.

Stereopticon or Slide Projectors. — The optical system of the familiar stereopticon or slide projector is similar to that of the motion picture projector, but the larger aperture, measuring $2\frac{3}{4}$ by $3\frac{1}{2}$ inches, is placed close to a pair of $4\frac{1}{2}$-inch-diameter plano-convex condensers, and for efficiency the source can be imaged in or near the objective. Moreover, no rotary shutter is required, and with the elimination of the accompanying loss of light, the requirements for the light source are not so severe; the usual light sources are employed in theatre projection, and the incandescent lamp for all portable and most other equipments. The objective lens is placed from 8 to 24 inches from the slide, depending on the picture size and projection distance, and for best efficiency the large diameter lenses, known as the No. 2 size, should be employed to transmit as much of the light beam emerging from the condenser as is possible.

Data on the incandescent lamps regularly used in slide and portable motion picture projectors are given in Table LXIII.

TABLE LXIII

INCANDESCENT PROJECTOR LAMP DATA

Watts	Volts	Bulb Diameter*	Overall Length	Base
250	110–120	$1\frac{3}{4}$ in.	$5\frac{5}{8}$ in.	Med. Screw
300	28–32	2 in.	$5\frac{5}{8}$ in.	Med. Screw
400	110–120	$2\frac{1}{2}$ in.	$5\frac{5}{8}$ in.	Med. Screw
1000	110–120	$2\frac{1}{2}$ in.	$9\frac{1}{2}$ in.	Mog. Screw

* Tubular bulb

COLLATERAL READING

Projection

NERZ, F., Searchlights (D. Van Nostrand Co., New York, 1907).

MARKS and CLERK, Electric Lighting for Motor Cars (Technical Publishing Co., London, 1910).

REY, J., and JOHNSON, J. H., The Range of Electric Searchlight Projectors (Constable & Co., London, 1917).

PUTNAM, G. R., Lighthouses and Lightships of the U. S. A. (Houghton, Mifflin & Co., New York, 1917).

BENFORD, F., Studies in the Projection of Light, Gen. Elec. Rev., **26,** 75 (1923).

PORTER, L. C., New Developments in the Projection of Light, Trans. I. E. S., **10,** 38 (1915).

PORTER, L. C., and POLLARD, F. Approach Lighting in Railway Signal Service, Gen. Elec. Rev., **25,** 422 (1922).

GARRARD, A., Motor Car Headlights, Ill. Eng., **14,** 87 (1921).

SUGG, C. R., DEMMINGTON, A. R., and PORTER, L. C., Basic Principles of Head Lamp Illumination, Elec. World, **62,** 741 (1913).

Report of Committee on Automobile Headlighting Specifications, Trans. I. E. S., **15,** 848 (1920).

BAIRD, C. W., and NOYES, E. P., History and Development of Searchlights, Jour. U. S. Artillery (1917).

Bech Searchlight, Elec. World, **64,** 181 (1914).

Sperry Searchlight, Elec., **78,** 512 (1917).

GROSJEAN, M., Les Projecteurs, Rev. Gen. de l'Elec., **6,** 445 (1919).

HIBBEN, S. G., Lighthouses and Light Vessels, Trans. I. E. S., **18,** 241 (1923).

CAMERON, A. D., The High-Intensity Arc Lamp, Trans. Motion Picture Engs. (Oct. 31, 1921).

CALDWELL, J. T., *et al.*, Motion Picture Projection, Trans. I. E. S., **13,** 232 (1918).

TAYLOR, J. B., The Projection Lantern, Trans. I. E. S., **11,** 414 (1916).

INDEX

G

Cady, Francis Elmore, 1876- ed.
Illuminating engineering, prepared by a staff of specialists for students and engineers; editors, Francis E. Cady, Henry B. Dates. Contributors, L. J. Buttolph, F. E. Cady [and others] New York, Wiley, 1925.
xiii, 486 p. illus., tables, diagrs., plates. 24 cm.